ATX Thermal Design Suggestions

Version 1.0

IMPORTANT INFORMATION AND DISCLAIMERS

Version 1.0, March 1999

Contents

Figures

Tables

1. Introduction

1.1 Revision History

Version	Revision History	Date
1.0	First release of ATX Thermal Design Suggestions	March 1999

1.2 Related Documents

1.2.1 Chassis and Motherboard

- *PC 98* and *PC 99 System Design Guides* from Intel Corporation and Microsoft Corporation
- *ATX Motherboard Specification* (see www.teleport.com/~ffsupprt)
- *Low Profile Fan Duct Motherboard and Chassis Specification* (see http://developer.intel.com/ial/sdt/fanduct.htm)
- *Low Profile Fan Duct System Ingredients Specification* (see http://developer.intel.com/ial/sdt/fanduct.htm)
- *Low Profile Fan Duct Design Guidelines* (see http://developer.intel.com/ial/sdt/fanduct.htm)
- *PCI Local Bus Specification*
- *PCI Bus Power Management Interconnect (PCI-PM) Specification*
- *Audio Codec '97 Component Specification*
- Data sheet–*Intel Pentium® II Processor* (Order Numbers 243335 and 243657)
- Data sheet–*Intel® Celeron™ Processor At 266 MHz, 300 MHz, 300A MHz, 333 MHz, 350 MHz, 400 MHz, and 450 MHz* (Order Number 243658)
- *Application Note (AP-586) Pentium® II Processor Thermal Design Guidelines* (Order Number 243331)
- *Direct Rambus™–Technology Disclosure* (see *www.rambus.com*)
- *Advanced Configuration and Power Interface Specification*
- *Accelerated Graphics Port (AGP) Design Guide*

1.2.2 EMC

- **U.S.:** *FCC Code of Federal Regulations (CFR) 47 Part 2 & 15, Class B*
- **Canada:** *DOC CRC c, 1374 Class B*
- **Europe:** *EN55022, Class B & EN50082-1 (Complying with the European Union's EMC Directive, 89/336/EEC)*
- **International:** *CISPR 22, Class B*

1.2.3 Acoustics Sound Pressure

Test setup and method are based on ISO 7779 “noise emitted by computer and business machines.”

1.2.4 Safety

- **U.S.:** *Underwriter Laboratories Inc. (UL-1950)*
- **Canada:** *Canadian Standards Association (CSA C22.2-950)*
- **Europe:** *EN60950 (Complying with the European Union’s EMC Directive, 89/336/EEC)*
- **International:** *International Electrotechnical Commission (IEC 950)*

2. Thermal Design Considerations

2.1 Introduction

The newest processors, chipsets, and memory pose significant thermal challenges to the system designer. As the market transitions to higher-speeds and greater bandwidths with enhanced features, the heat generated by these devices continually increases, placing complex cooling demands on the system.

The goal of this section is to provide a brief introduction to:

- General thermal design principles, including estimating the airflow required for a given heat load
- The concept of thermal resistance and its application to heat dissipation through integrated circuits and heat sinks

Most systems depend on tube axial fans to cool components, so fan size, airflow and impedance, and fan location will be emphasized. The correct fan size cannot be chosen without knowing the chassis airflow impedance. A chassis with greater airflow impedance requires a larger fan to move a given amount of air, and likewise a well flowing chassis requires a smaller fan to move the same amount. Minimizing airflow obstructions and optimizing airflow patterns including the power supply are important, so factors affecting chassis airflow and determining the system characteristic curve will be explained.

The power supply usually has the largest impact on system level cooling because the power supply fan is most often the only fan in system designs. Therefore, power supply selection is critical to proper system performance. Selecting a well-designed power supply can *double* the system's airflow, allowing more flexibility in the chassis design.

Power supplies and/or motherboards with advanced thermal management techniques such as fan speed control and Advanced Configuration and Power Interface (ACPI) are becoming more popular to control both acoustics and component temperatures. If the power supply or system fan is speed-controlled, the thermal design should account for various load and temperature combinations.

Although heat sink selection is explained in greater detail in the Pentium® II processor and Intel chipset application notes, passive, active, and liquid-cooled heat sinks and manufacturing methods and their relative cooling ability are briefly mentioned here for reference.

Add-in cards and peripheral cooling requirements are often ignored or forgotten during the chassis design. The newest AGP graphics cards and DVD drives, for example, dissipate significantly higher power than previous generations. Future graphics controllers have the potential to increase to 15 W. These components now require some airflow rather than the previous natural convection cooling scheme. It is important to understand what requirements the peripherals and add-in cards have that may be included in the system.

Acoustics are an important consideration, because a cool-running system may not always operate quietly. A basic guideline requires that systems operating with less than 300 W must be quieter than 45 dBA at 23 °C. However, quieter systems operating at less than 45 dBA are possible with design goals of 35 dBA.

After the system design is complete and prototypes are available for evaluation, the system must be tested to ensure it meets specified criteria for component temperatures and required airflow. Various techniques are available to measure temperature and airflow. The most common device used to measure component temperatures is the thermocouple. Hot-wire anemometers, static pressure tubes, and flow chambers are some of the tools used to measure airflow. Whichever method is selected, careful setup is required to provide accurate results.

Because of the complexity of varying chassis designs, modifications may be necessary to some of the suggestions given here to achieve an effective cooling scheme. The system's cooling scheme must ensure that all components and peripherals remain within their specified operating temperature ranges. In addition to the suggestions discussed in this document, the designer should be aware of the system-level requirements described in the *PC 99 System Design Guide*.

2.2 Thermal Design Principles

2.2.1 General Principles

The first step in defining an acceptable cooling solution is to estimate the total airflow required to cool the entire system (not just the processor).

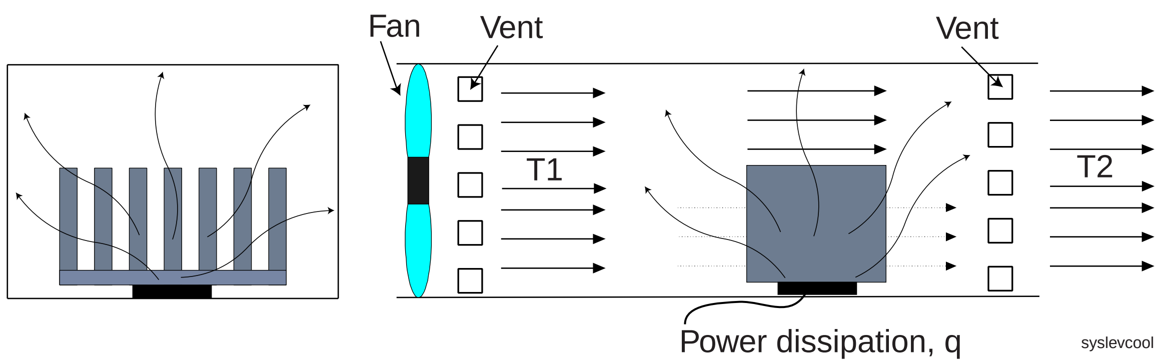

Figure 2.1: Simplified System Component Cooling

To do this, we refer to the 1st Law of Thermodynamics (Conservation of Energy) for a steady state, steady flow process, as follows[1]:

$$_1q_2 \equiv \Delta h + \Delta K.E. + \Delta P.E. + _1w_2 \quad \text{(kJ/kg)}$$

Where:

q = heat dissipated in the system

Δh = change in enthalpy

$\Delta K.E.$ = change in kinetic energy

$\Delta P.E.$ = change in potentiall energy

and, w = work done by the system

Assume the change in kinetic and potential energy of the airflow is zero, and no work is performed by the system. Then factoring in the mass flow of the air, this equation can be rewritten as[1]:

$$_1q_2 \equiv \dot{m}\Delta h = \dot{m}c_p(T_2 - T_1) = \dot{v}\rho c_p(T_2 - T_1)$$

now, solving explicitly for volumetric airflow, we have the equation[1]:

$$\boxed{\textbf{Equation 1:} \quad \dot{v} = \frac{_1q_2}{\rho c_p (T_2 - T_1)}}$$

[1] *Fundamentals of Engineering Thermodynamics*, Moran, M.J. & Shapiro, H.N., pp. 123-128.

The airflow of a system can be significantly different from the air flow of just the power supply or system fan. A system can, in reality, experience somewhere between 30% to 50% restriction of airflow due to system impedance. Therefore, a fan capable of providing even more airflow than Equation 1 indicates is needed to overcome the system impedance and cool the system. For well-designed chassis an airflow increase of approximately 30% is needed to account for the system impedance. If possible, use the measured DC power of the system as the heat load in Equation 1. The AC power can be used as an approximation, but the inefficiency of the power supply makes the AC power value larger than the DC power value, resulting in an inaccurate airflow requirement. Both ρ and c_p are evaluated at room temperature; a correction factor is necessary for other ambient air conditions.

2.2.2 Thermal Circuit

There are three fundamental modes of heat transfer: conduction, convection, and radiation. Heat sinks are used to increase the effectiveness of the heat transfer from the hot solid surface to the cool ambient through conduction and convection. This is accomplished primarily by increasing the effective surface area that is in direct contact with the coolant, air. Because air is a poor conductor of heat, it is therefore important to keep the air moving to increase the convective heat transfer. The increase in component surface area allows more heat to be conducted from the component silicon and then dissipated into the system environment. This lowers the device operating temperature, ultimately ensuring the device temperature remains well below its maximum allowable temperature specification.

A typical example of a thermal model, the electric circuit analog to heat conduction, is shown in Figure 2.2. The goal of this section is to provide a basic understanding of fundamental heat sink concepts. Some key terms are defined below:

T_j, T_c, T_s and T_a - The temperatures at the junction, component case, heat sink base, and ambient air.

q - The maximum electronic power dissipation of the electronic component.

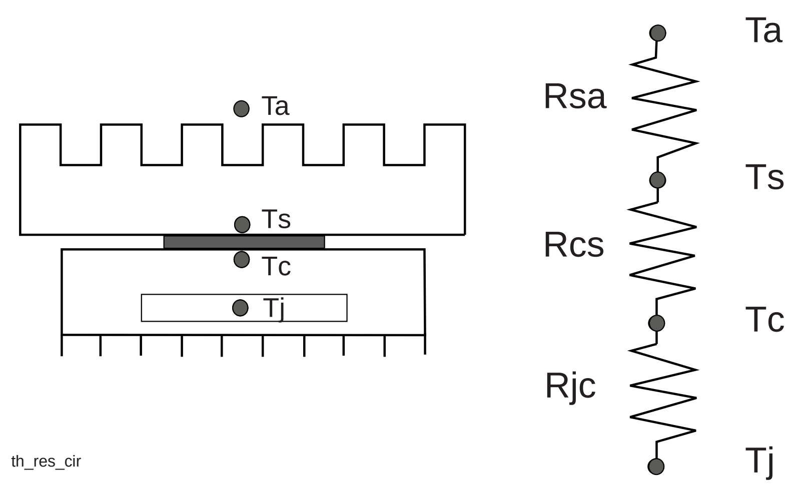

Figure 2.2: Thermal Resistance Circuit

The best figure of merit for heat sink performance is the overall thermal resistance R_{ja}. In this model the heat is assumed to flow serially from the junction, through the case and heat sink, to the ambient air. The overall thermal resistance is defined as follows[2]:

$$R_{ja} = R_{jc} + R_{cs} + R_{sa} = \frac{(T_j - T_c)}{q} + \frac{(T_c - T_s)}{q} + \frac{(T_s - T_a)}{q}$$

R_{jc} represents the thermal resistance between the junction and the case of the component and is typically not under the control of the system designer. R_{cs} represents the resistance of the thermal interface material, and R_{sa} represents the heat sink thermal resistance between heat sink and air. The smaller the resistance value, the more power a device can dissipate without exceeding its junction temperature. In reality, the flow of heat is three-dimensional (not one-dimensional as shown above), but the model shown above still works fairly well.

The *interface resistance* (R_{cs}) depends on many factors including the surface flatness, the surface finish, the mounting pressure, the contact area, and the type of interface material used along with its thickness.

The interface resistance is often expressed as[2]:

$$R_{cs} \cong \frac{t}{\kappa A}$$

where "t" represents the material thickness, "A" represents the contact area, and "κ" is the material thermal conductivity.

The *heat sink resistance* is a function of the airflow and the effective surface area of the heat sink[2]:

$$R_{sa} = \frac{1}{h_c A} \text{ in } \frac{^\circ\mathrm{C}}{\mathrm{W}}$$

The value of the heat sink resistance can be reduced by increasing the effective surface area of the heat sink, A, or by increasing the convective heat transfer coefficient, h_c. Care must be exercised here as h_c is very sensitive to airflow. If the added surface area chokes off the airflow through the heat sink, the value of h_c may be reduced so much that the product of $h_c A$ actually decreases.

A quick estimate of the necessary heat sink performance can be found in the following manner. For the systems we commonly deal with, the maximum processor case (or heat plate) temperature is specified along with the maximum processor dissipated power. Initially, ignore the thermal interface resistance and estimate the heat sink resistance using[2]:

$$R_{sa} = \frac{T_c - T_a}{Q} \left(\frac{^\circ\mathrm{C}}{\mathrm{W}} \right)$$

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[2] *Fundamentals of Heat and Mass Transfer*, Incropera, F.P. & Dewitt, D.P., pp. 80-84.

Radiation effects are typically ignored initially for forced convection cooling schemes. However, radiation is important in natural convection cooling schemes and may be responsible for up to 25% of the total heat transfer. Unless the component is facing a hotter surface nearby, the heat sink surface should be painted or anodized to enhance radiant heat transfer.

2.3 Fans

Fans implement the forced convection approach to cooling. Stated simply, the greater the air velocity over the surface of a component, the greater the heat transfer from that component. Fans may differ in their characteristics, and therefore a prudent choice of fans can optimize both airflow and acoustics.

Fans can be used to blow air into (pressurize) or out of (evacuate) the chassis depending on which direction they are installed.

<u>Pressurizing</u> the chassis with a fan delivers cool room ambient air onto any location where it is needed to enhance heat transfer.

<u>Evacuating</u> induces a negative pressure (relative to room ambient) inside the chassis, which draws air in through the vents. This inflow of air from the vents is pulled through the chassis across hot components and is exhausted out the fan.

2.3.1 Fan Types

There are several types of fans to consider for system cooling: *tube axial* and *radial*. Tube axial is the most commonly used type throughout the computer industry. Axial fans typically cost less and generally push more air at a common back pressure. Radial fans, however, are much less susceptible to variations in back pressure and often have restricted openings that can focus needed cooling air directly at hot components. When power dissipation is highly concentrated, a radial fan (blower) may be a reasonable option. Figure 2.3 shows a typical axial fan characteristic curve and the effect of running the fan at different speeds (or voltage levels).

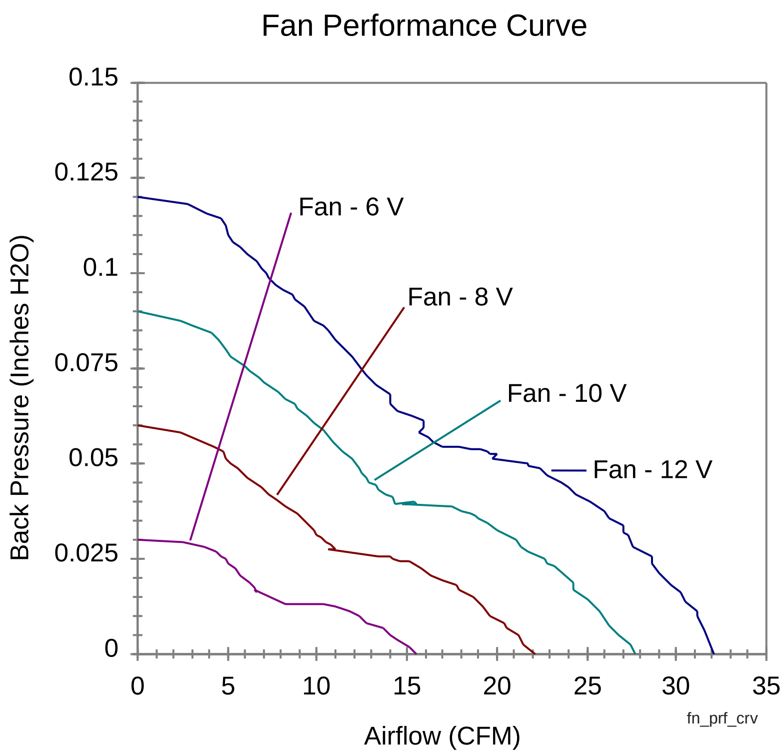

Figure 2.3: Typical Axial Fan Characteristic Curve (for Various Voltages)

2.3.2 Parallel and Series Fan Combinations

Multiple fans can be used in two combinations, parallel and series.

- Two fans in parallel, $Q = Q_1 + Q_2$ at zero back pressure
- Two fans in series, $p = p_1 + p_2$ at zero airflow

An example of a parallel fan combination is a system fan and a power supply fan both either pressurizing or evacuating a chassis. Ideally, a parallel fan configuration doubles the system airflow. An example of a series fan combination is a system fan blowing air into the chassis and a power supply fan exhausting air from the chassis. Ideally, a series fan configuration doubles the system's ability to overcome built-up back pressure. In reality, because of venting, leakage, and design compromises, when we employ multiple fans, we often are implementing a combination series/parallel configuration. The effect of employing series/parallel fan configurations is shown in Figures 2.4 and 2.5.

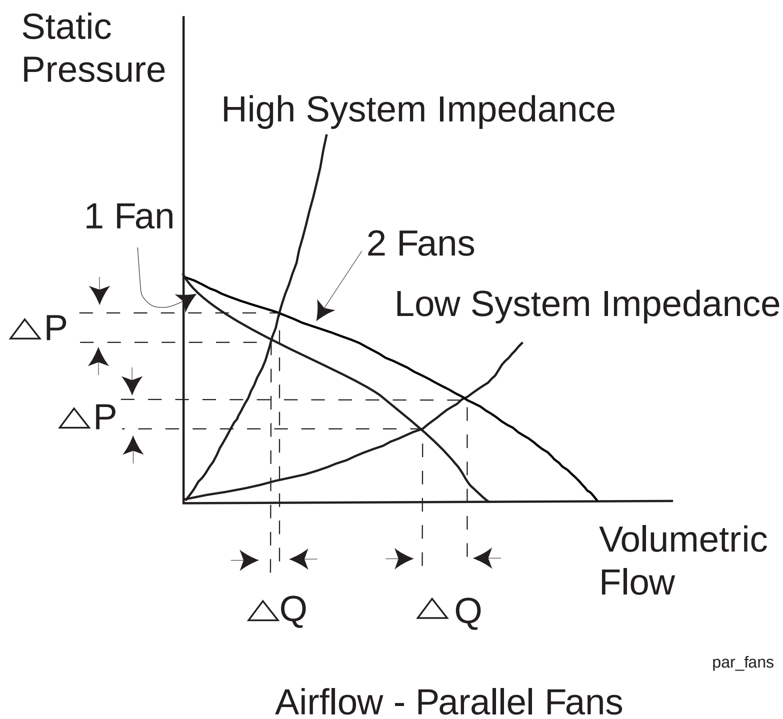

Figure 2.4: Performance Curves for Parallel Fan Combination

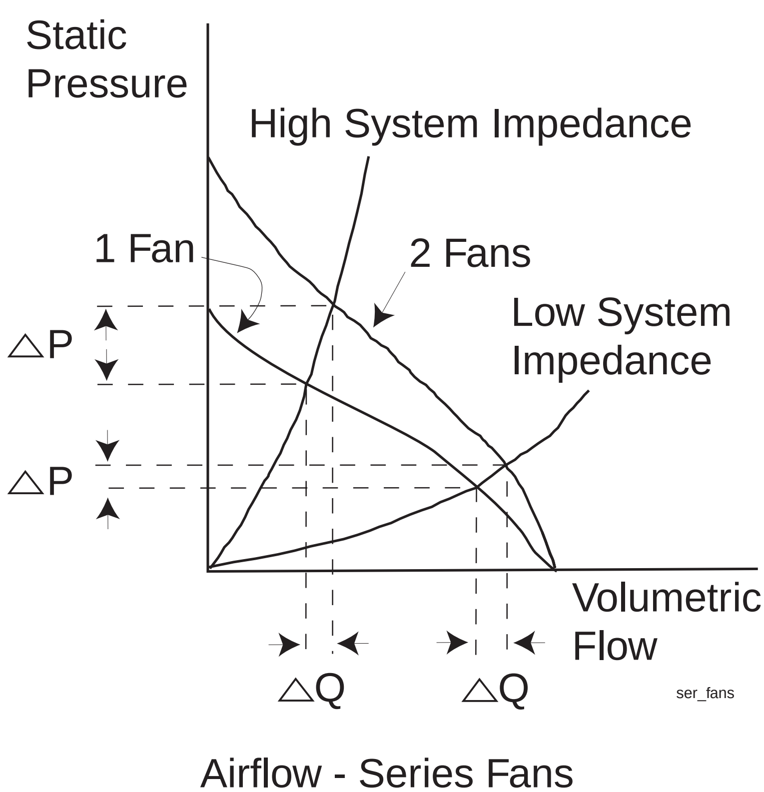

Figure 2.5: Performance Curves for Series Fan Combination

Employing multiple (identical) fans in a system does provide some marginal increase in airflow. The exact amount depends on many factors, including fan speed and configuration, as well as chassis airflow impedance. If the fans are not identical, then the figures will change slightly, but the trends will be similar. The general rule is, if the chassis has high impedance, place the fans in series. If the chassis has low impedance, place the fans in parallel.

2.3.3 Fan Relationships

The relationships in Tables 2.1 and 2.2 below describe how airflow, pressure, power, and sound pressure vary with fan speed and with variations in both fan speed and fan diameter.

Table 2.1: Fan Laws: Variable Speed - Constant Diameter

Description	Relationship
Airflow vs. R.P.M.	$Q_1/Q_2 = n_1/n_2$
Pressure vs. R.P.M	$p_1/p_2 = \left(n_1/n_2\right)^2$
Power vs. R.P.M.	$h.p._1/h.p._2 = \left(n_1/n_2\right)^3$
Sound Pressure vs. R.P.M.	$SPL_2 - SPL_1 = 50 Log\left(n_2/n_1\right)$

Table 2.2: Fan Laws: Variable Speed - Variable Diameter

Description	Relationship
Airflow vs. R.P.M.	$Q_1/Q_2 = \left(D_1/D_2\right)^3\left(n_1/n_2\right) = \left(D_1/D_2\right)^2\sqrt{p_1/p_2}\sqrt{\rho_2/\rho_1}$
Pressure vs. R.P.M	$p_1/p_2 = \left(D_1/D_2\right)^2\left(n_1/n_2\right)^2\left(\rho_1/\rho_2\right)$
Power vs. R.P.M.	$h.p._1/h.p._2 = \left(D_1/D_2\right)^5\left(n_1/n_2\right)^3\left(\rho_1/\rho_2\right)$

Obviously all tube axial fans used in systems today are of constant diameter from the front of the fan to the back of the fan. Key points of constant diameter fan relationships to remember are:

- Airflow increases linearly with speed
- Pressure increases with the square of the speed
- Power increases with the cube of the speed
- Sound pressure varies with the log of the speed

Increasing the fan speed to increase airflow results in a much larger increase in pressure. If increased airflow is desired, consider increasing the fan diameter from 80 mm to 92 mm instead of increasing the speed. Cost must be considered because generally 92 mm fans are more expensive than 80 mm fans. However, a 92 mm fan operating at the same flow rate as an 80 mm fan is approximately 6 dBA quieter.

2.4 Airflow Impedance

Air flowing through a computer chassis encounters frictional resistance, known as airflow impedance. This impedance creates a pressure drop in the chassis that roughly obeys Bernoulli's principle and is found to vary approximately with the square of the velocity, or since $Q = A \cdot v$, with the squared volumetric airflow. Plotting pressure loss versus volumetric flow rate, which results in the system characteristic curve, can show the relationship. The point about this behavior is that if one data point on the curve is known, the system's overall performance can be predicted. When the system characteristic curve is superimposed on the fan performance curve, the operating point of the system is specified explicitly. The concept is demonstrated in Figure 2.6 where different power supplies were compared with different chassis.

Here are more guidelines to consider when assessing system airflow issues:

- The operating point should be chosen to the right of the local maximum peak on the fan pressure curve to avoid pressure and volumetric flow rate fluctuations.
- Choose a fan with a steep characteristic curve to maintain constant volumetric flow even with variable system impedance.
- Avoid obstructions near the inlet and exhaust of the fans, as these tend to decrease airflow and increase system noise.
- Use fan speed control whenever possible and cost effective. This yields adequate thermal margin and provides a significant acoustic advantage.
- Power supply cables and drive signal cables should be kept short and properly folded.

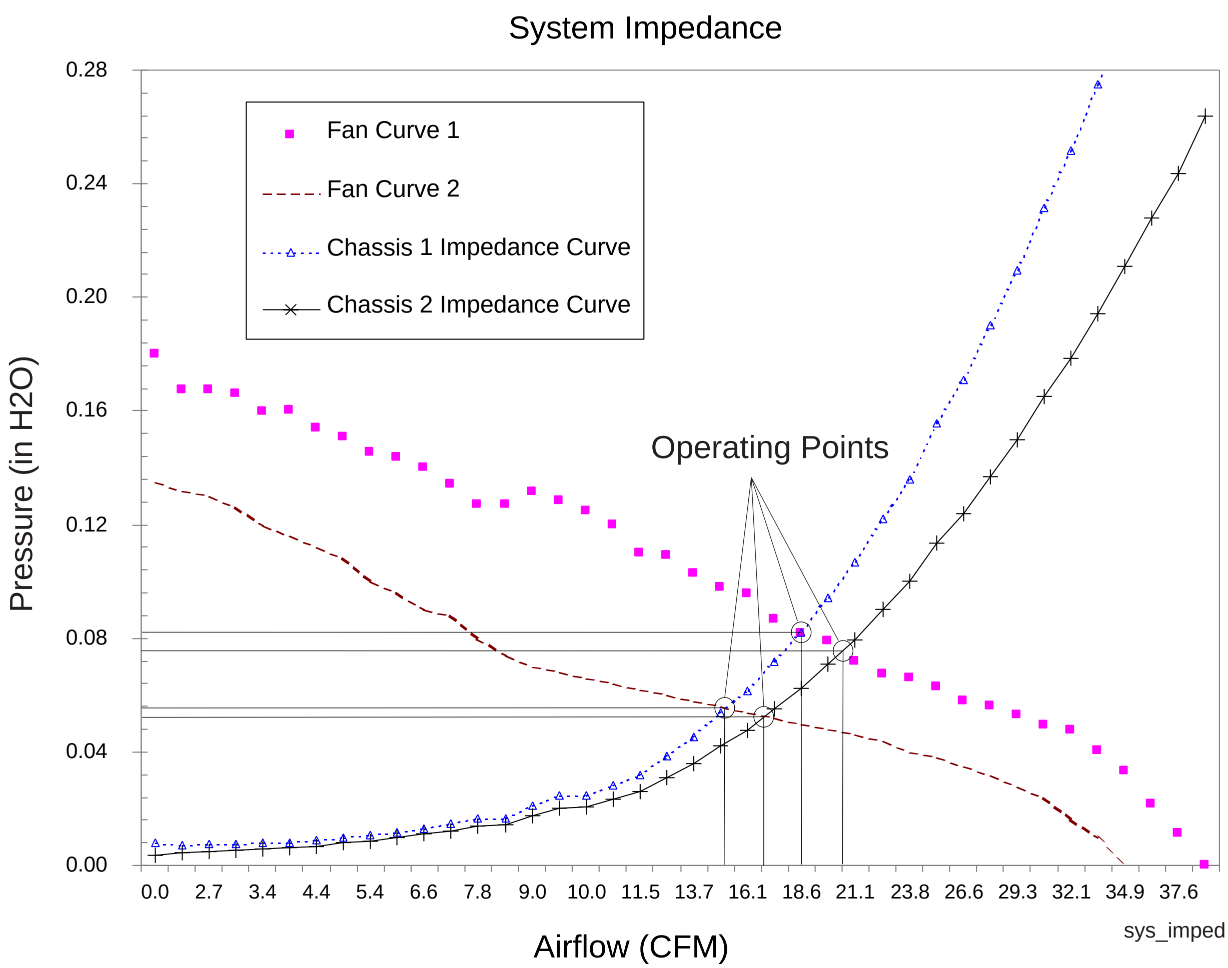

Figure 2.6: System Characteristic Curve

2.5 Power Supply Characteristics

The power supply is among the most influential components in the system cooling design. The chassis venting scheme may be well designed, but if the correct power supply is not selected, the system will not cool the processor, chipset, memory, and/or the peripherals. The power supply and any system fans must provide enough airflow to cool the system heat load as outlined by Equation 1 in Section 2.2.1.

Key considerations when selecting/designing a power supply:

- Evacuate the chassis (rather than pressurize it) with the power supply fan. The advantage of evacuating the chassis is that cool room ambient air can be delivered (via vents) to any location where it is needed to enhance heat transfer. Evaluation has shown evacuating produces greater cooling than pressurizing using the same fan with proper implementation.
- All vents should have a minimum free area ratio of 50%. Consult the EMI design guidelines to ensure vent designs comply with all applicable regulations.
- Implement a wire fan grille rather than the common stamped sheet metal designs, because the airflow impedance is reduced.
- Minimize the power supply component height to keep the profile low and streamlined. This reduces the overall supply impedance while still maintaining effective power supply cooling.
- Keep the power supply cables short to reduce their airflow obstruction.
- Select a power supply with the highest airflow possible. A well-designed power supply has lower airflow impedance, allowing a slower, quieter fan for cooling. The poorly designed supply requires a faster, louder fan to maintain the same airflow because of its greater airflow impedance.

Figure 2.7 depicts the power supply impedance curve and the associated fan curve of three different power supplies. The point where the fan curve intersects the power supply impedance curve defines the operating point. Power supplies 1 and 2 (ATX and PS/2 style, respectively) flow approximately twice as much as power supply 3 (ATX style). Note power supply 3 has a slower fan <u>and</u> higher airflow impedance, resulting in the lower airflow.

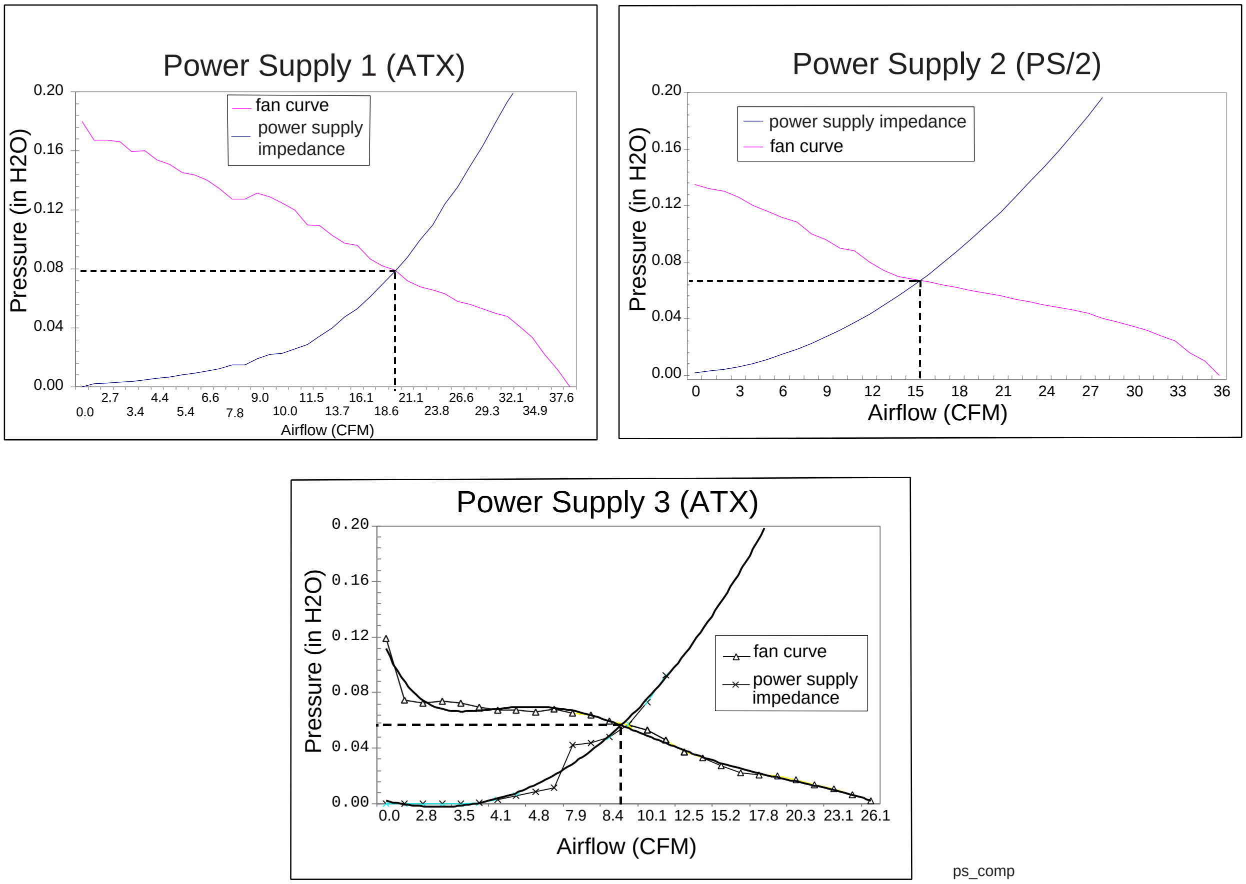

Figure 2.7: Power Supply Performance Comparison

2.5.1 Power Supply Considerations

There are several types of power supplies to consider within an ATX chassis. A power supply should have maximum airflow to cool both the power supply and key components inside the system such as the processor, chipset, memory, AGP, and peripheral components. The exact venting location, geometry, fan selection, airflow, and overall power supply impedance will vary, depending on the complete system solution implemented. Two different power supply locations are currently used in most ATX chassis. These are the core logic and top, rear-mounted power supply locations.

2.5.1.1 Core Logic Mounted Power Supply Location

Mounting the power supply directly over the core logic components (lower right corner of the example mini-tower chassis) is one possible power supply location in the ATX system. In this configuration, the power supply evacuates the chassis by pulling air in from the front, top, or side vents and evacuating this air through the power supply and out the back of the chassis. The air should pass across the core logic components before exiting through the power supply. In this configuration, it is more plausible to cool the core logic components without the need of an active heat sink. Figure 2.8 shows an example of an ATX style chassis with a core logic mounted power supply.

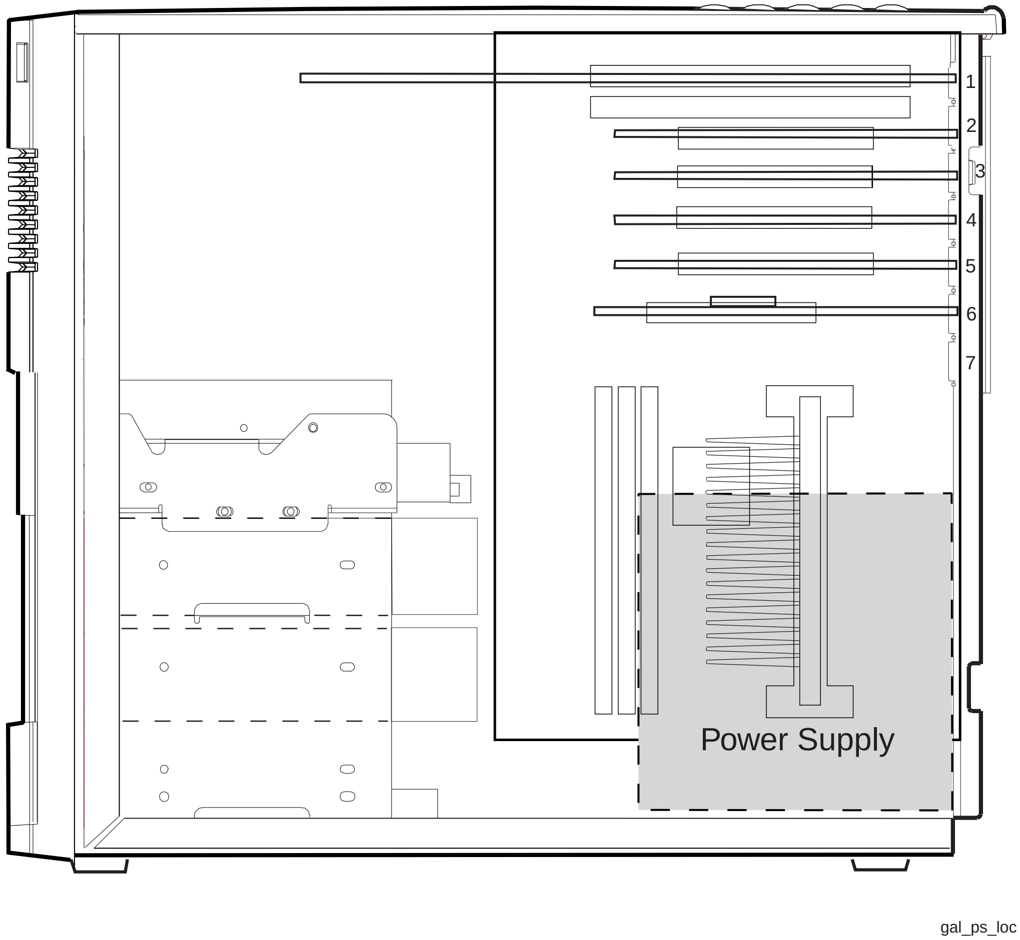

Figure 2.8: Core Logic Mounted Power Supply Location

2.5.1.2 Top, Rear-mounted Power Supply Location

Mounting the power supply at the top, rear of the chassis above the motherboard is another possible power supply location in the ATX system. In this configuration, the power supply evacuates the chassis by pulling air in from the front or side vents and evacuating it through the power supply and out the back of the chassis. The airflow path is less likely to cross directly over the core logic components before exiting through the power supply. Therefore, this configuration is less likely to cool the core logic components without the need of alternative cooling solutions (active heat sink, ducting, etc.). Figure 2.9 illustrates a typical top, rear-mounted power supply chassis.

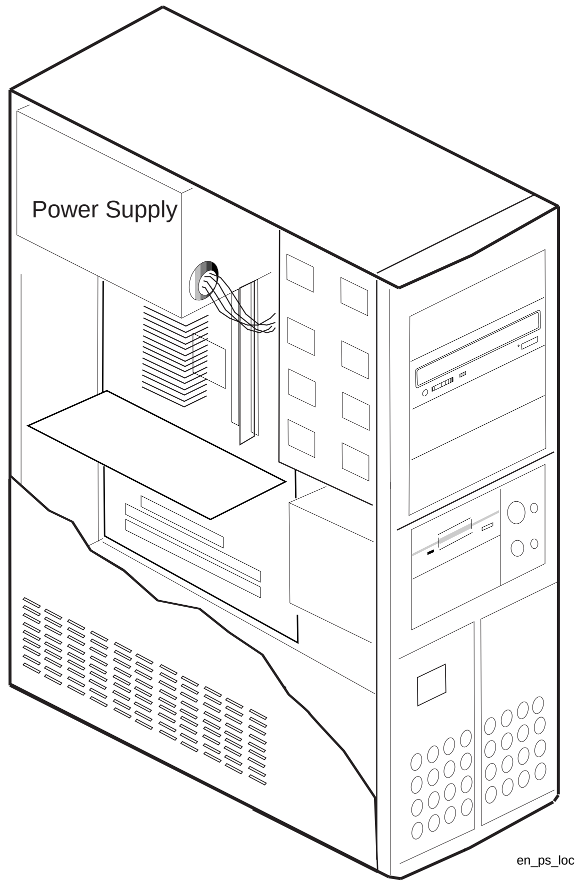

Figure 2.9: Top, Rear Mounted Power Supply Location

2.6 Advanced Thermal Management

2.6.1 Fan Speed Control

Fan speed control allows a system to vary its airflow as changes in load and/or temperature occur. Fan speed control circuit ideas have been around for some time but were not always used possibly due to their cost and increase in system complexity. However, computers are now incorporating hotter processors and peripherals requiring greater airflow while at the same time customers are requesting quieter systems. These competing design constraints have led to a resurgence of fan speed control options. Acoustically, fan noise increases directly with fan speed and is a major contributor to total system noise. For systems that incorporate fan speed control, proper speed regulation is important, because it is desirable to achieve low acoustic levels without overheating components. The fan speed control circuit should be designed such that it monitors temperature at a component (or several components) and adjusts fan speed as necessary to maintain the required thermal margin.

Three distinct design options should be considered:

Discrete Digital Switches

If airflow requirements can be confined to a discrete number of fan speeds, this option is the cheapest and easiest to implement.

Analog Linear Control Between Two Guard Bands

For fans used in most systems, speed control can usually be accomplished by varying the voltage level at the fan's power terminals (many power supplies/fans come equipped with this feature). An operating voltage range example for an 80 mm, 30 CFM, .14 amp fan might be 8 V to 12 VDC, corresponding to 1650 rpm and 2500 rpm, respectively.

Pulse Width Modulation Schemes

This is a digital variation on the second option. Consider this option if the fan needs to be varied from some minimum speed (presumably set for the system sleep state) to some maximum speed (needed for a fully loaded active state).

No matter which fan speed control method is chosen, the following issues should also be noted:

- The location where temperature is monitored is important (sensing critical component case temperatures is recommended). Whatever location is selected, it should represent the thermal state of the entire system.
- A driver circuit for the fan must be included.
- Some fans need a minimum starting voltage (see fan specification).
- Fan noise increases with fan operating voltage (speed). Minimum fan noise occurs at maximum fan power efficiency (see fan specification).
- If the fan is not speed-controlled, at what voltage (speed) level is it operating? In this case since it is not possible to vary fan speed, choose the lowest rated fan speed that will cool the system under worst-case loading/temperature conditions.
- Power supplies that have motherboard-controlled fan speed circuitry should include an override feature to prevent power supply failures.

If fan speed control is implemented, the thermal design should account for various load and temperature combinations. Component temperatures should be verified to ensure the thermal design meets specification under these load and temperature combinations.

2.6.2 Advanced Configuration and Power Interface (ACPI)

ACPI provides the control policy for a PC to measure temperatures of critical internal components. This allows local temperature-sensing circuits to be read by the BIOS and operating system. The sensing circuits may use device-mounted thermistors, thermocouples, or temperature diodes. Critical "triggers" can be programmed to cause alarm events that instigate a (graded) cooling policy.

Cooling policies can be either "Passive" (where performance is limited to reduce heat generation) or "Active" (where fan speed or on/off control is used to limit temperature as heat increases). The policies can be mixed and can be used in any order.

In Figure 2.10 below, as the processor temperature starts to rise, the operating system senses a critical temperature and starts to limit power dissipation. If temperature continues to rise, the cooling fan is switched on (slow). Any further increases in temperature result in the operating system increasing the fan speed. If the fan speed maximum is reached and the temperature continues to rise, the system shuts down entirely to prevent damage.

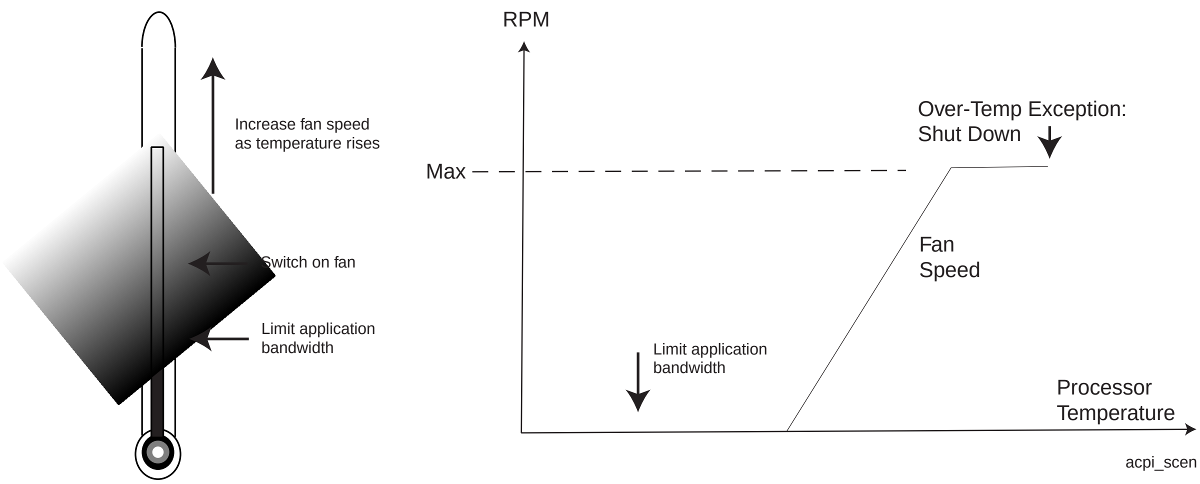

Figure 2.10: Example ACPI Scenario

2.7 Heat Sinks

2.7.1 Introduction

This section provides an overview of heat sink types and categories. Refer to the *Pentium® II Processor Application Note - Thermal Design Guidelines* and the corresponding thermal application note for the chipset for a detailed discussion concerning heat sink selection. As with other key system components, the selection process for thermal management components includes consideration of such issues as cost, ease of assembly, manufacturability, and upgradability as well as functional performance.

2.7.2 Heat Sink Categories

One way to classify heat sinks is by the cooling mechanism used to remove heat from the heat sink itself.

- *Passive Heat Sinks:* Passive heat sinks are used in natural convection applications and applications where heat dissipation does not rely on a specified local air velocity.
- *Active Heat Sinks:* These heat sinks employ dedicated fans, configured for either impingement or cross flow.
- *Liquid Cooled Heat Sinks:* These heat sinks typically incorporate tubes-in-block designs or milled passages in brazed assemblies channeling cooling liquids such as water or oil.
- *Phase Change, or Recirculating, Heat Sinks:* These include two-phase systems that employ a boiler and condenser in a passive, self-driven, mechanism. Heat pipes are the most common example of this type of heat sink. They passively transfer heat from a source to a sink where the heat is dissipated. The heat pipe is an evacuated vessel that is partially filled with a minute amount of water or other working fluid. As heat is directed into the device, the fluid is vaporized creating a pressure gradient in the pipe forcing the vapor to flow along the pipe to the cooler section where it condenses, giving up its latent heat of vaporization. The working fluid is then returned to the evaporator by capillary forces developed in the heat pipe's porous wick structure, or by gravity.
- *Thermoelectric coolers (TECs):* These are solid state heat pumps that use the Peltier effect. During operation, DC current flows through the TEC causing heat to be transferred from one side of the TEC to the other, creating a “cold side” and a “hot side.” However, the heat from the “hot side” and the heat from the TEC inefficiencies must be removed from the system.

2.7.3 Heat Sink Types

One can also classify heat sinks in terms of manufacturing methods and their final form.

- *Stampings:* Stamped heat sinks provide a low cost solution to low power density thermal problems. Copper or aluminum sheet metal can be stamped into any desired shape. Attachment features and interface materials can be added with ease during the manufacturing process.
- *Extrusions:* Molten metal is drawn through a die in the desired direction of the heat sink fins and then cooled. Extruded heat sinks allow the elaborate formation of two-dimensional shapes capable of dissipating large heat loads. This is the type most commonly attached to processors. Practical aspect ratios range from 5 to 8.
- *Bonded/Fabricated Fins:* Most air-cooled sinks are convection limited. Bonded fin heat sinks maximize available heat transfer surface area by bonding planar fins on a grooved, extruded base plate. Due to the unique manufacturing process, aspect ratios (fin height to width ratio) of 20 to 40 can be easily achieved, greatly increasing the heat sink's cooling capacity.
- *Castings:* This technology is used in high density pin fin heat sinks that provide maximum performance when using impingement cooling.
- *Folded/Convoluted Fins:* Corrugated sheet metal is bonded to an extruded base plate. The heat sink surface area is increased due to the folds, thus the overall thermal performance improves.

2.8 System Airflow Patterns

Airflow management is critical to ensure that adequate localized airflow is provided to all components in the system. The processor, chipset, memory, and AGP graphics typically require more airflow than the other peripherals or add-in cards, so care must be taken to properly distribute the airflow among components.

An important consideration in airflow management is the temperature of the air flowing over the components. Heating effects from add-in cards, memory, and peripheral devices increase the internal air temperature thus reducing the cooling efficiency of the air. The recirculation of air can also contribute to increased internal air temperatures.

For example, a system with minimal venting and a low-flow power supply fan will have restricted airflow through the system. Restricted airflow results in lower system air speeds and often, stagnant air pockets. This can directly lead to an increase in the overall internal air temperature. The warm, slow air creates less effective component cooling that requires additional cooling mechanisms such as fan heat sinks rather than passive heat sinks. The well-designed system allows less expensive, passive heat sinks to be used on the processor and possibly no heat sinks on other components.

Ducts can be designed to isolate key integrated circuit devices (such as processors and chipsets) from the effects of system heating (such as add-in cards and peripherals). Air provided by a fan or blower can be channeled directly over the key integrated circuit

devices, or split into multiple paths to cool multiple integrated circuit devices. This method can also be employed to provide some level of redundancy in a system requiring redundant capabilities for fault tolerance. This is accomplished by channeling air from two or more fans through the same path across a processor. Each fan, or each set of fans, must be designed to provide sufficient cooling in the event that the other has failed.

When ducting is used, it should direct the airflow evenly from the fan across the entire component. The ducting should be accomplished, if possible, with smooth, gradual turns as this will reduce airflow impedance. Sharp turns in ducting should be avoided. Sharp turns increase friction and drag and will greatly reduce the volume of air reaching the key integrated circuit devices.

The three main factors contributing to the distribution of airflow in a system are:

- Power supply characteristics, including location, impedance, and fan size can heavily influence system airflow patterns.
- Vents in the chassis must be placed to allow in-rushing cool ambient air to cross hot components and exhaust out the power supply in an evacuating configuration. Alternatively, vents can be placed to allow hot air to escape the system in a pressurized configuration.
- If a system fan is used in addition to the power supply fan, the location and the flow direction can be important. The use of a system fan can differ depending on the form factor. Most ATX systems use the system fan to increase the amount of cool external air that is flowing into the chassis. It is not normally recommended to have this fan operate at a flow rate that exceeds the power supply flow rate. Therefore the system's airflow pattern constitutes an evacuating configuration instead of a pressurizing configuration.

In an ATX system, the single chamber design makes power supply choice more critical than in some other platform configurations. The power supply is most often located at the side of the chassis above the core logic components, or at the top, rear of the chassis. Also, the core logic is usually not near a front system fan, possibly requiring ducting or other schemes to ensure proper cooling.

ATX airflow pattern key features and considerations:

- The single chamber system approach relies on the power supply more to cool the core logic and less on a system fan.
- The system is evacuated with the power supply fan and can possibly be pressurized with a front system fan (series combination). This increases the system's total airflow.
- The add-in cards do not receive high airflow, so natural convection dominates forced convection. The AGP graphics accelerator can be difficult to cool and additional venting may be required to maintain the ambient air temperature below the specification.
- Pressuring the system can result in increased ambient air temperatures at add-in card and peripheral locations.
- A second fan, located in the front bezel, is not normally required if venting is properly designed.

Figures 2.11 and 2.12 show the airflow patterns in the two most typical ATX systems.

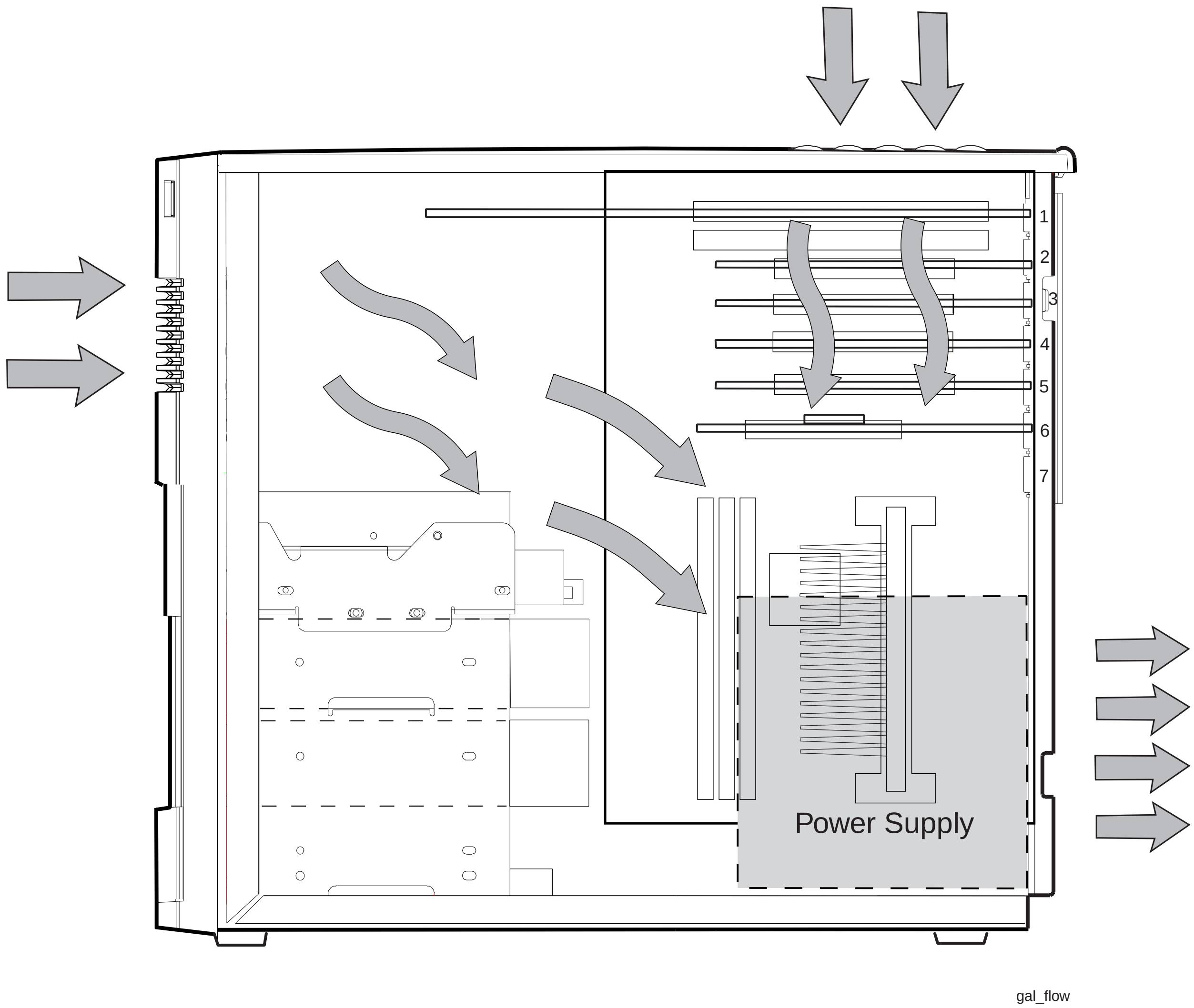

Figure 2.11: Mini-Tower ATX Airflow Pattern

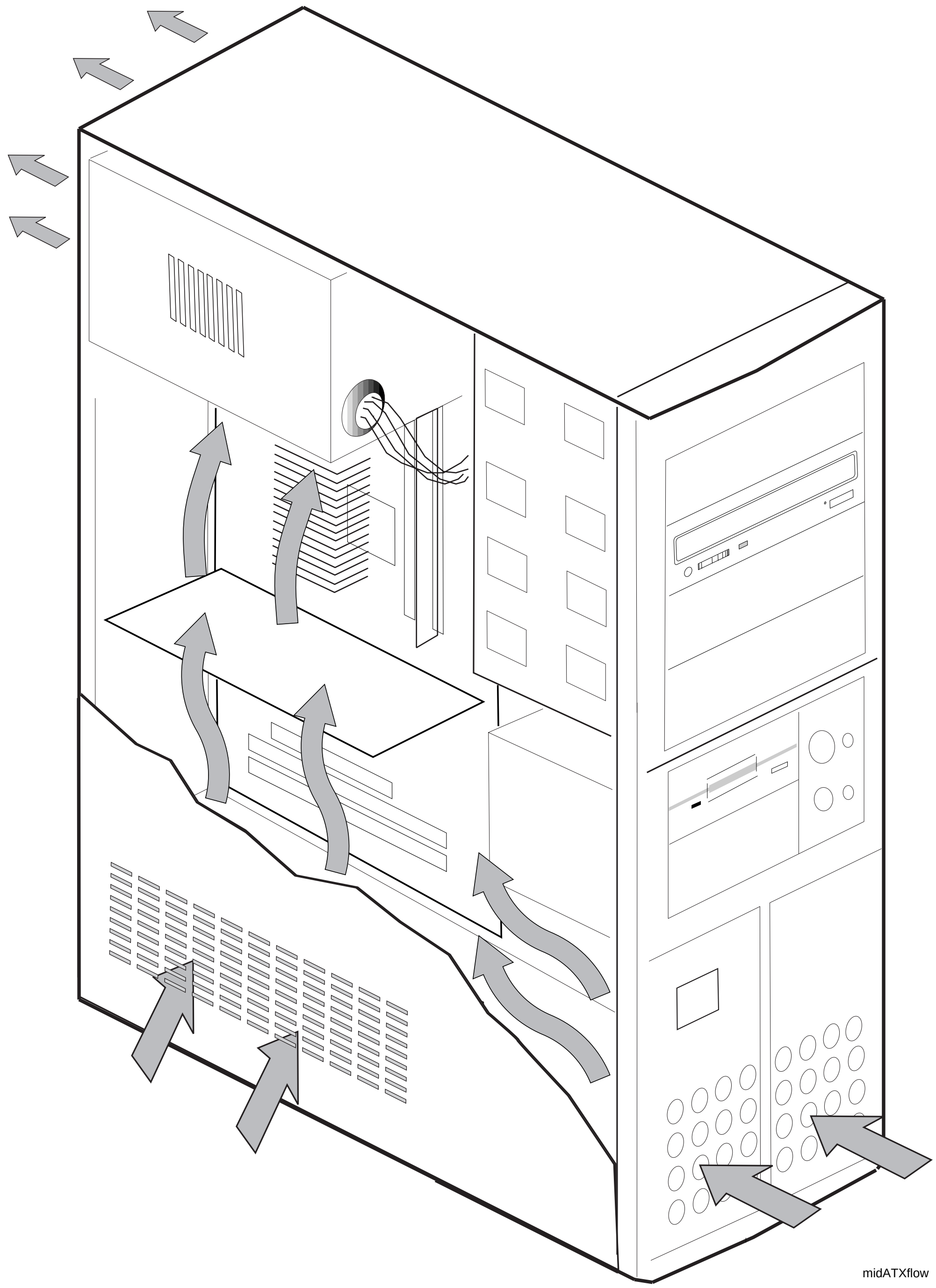

Figure 2.12: Mid-Tower ATX Airflow Pattern

2.8.1 Chassis and Bezel Venting

Proper venting is a key element in any good thermal design. A balanced approach to vent location and pattern type is a critical factor in this design. Implementing an insufficient amount of open area to the exterior of a chassis does not allow enough air into the system for adequate cooling. Implementing too much venting can allow for air to bleed from the chassis thus decreasing the air velocity across the system's hot components. The reduction in local air velocities at these components results in less forced convective heat transfer.

To increase airflow through the system, all system accessory components (cables, wires, sheet metal, etc.) should present the lowest possible airflow impedance. Also, generous venting into and out of the power supply is necessary because virtually all air entering the system must exit via the power supply.

(NOTE: To eliminate possible electromagnetic compliance issues, neither the maximum vertical nor maximum horizontal dimensions of ventilation apertures, I/O ports, and open areas along chassis seams should be less than 1/20th of a wavelength of the highest harmonic frequency of interest.)

Key considerations:

- *Power Supply* – In the ATX form factor the power supply fan removes the majority of the airflow out of the system. Therefore, the airflow capability of the power supply is very important.
- *Front bezel venting* – The bezel vent area should be as large as possible because it serves as the main air inlet for the system. **It is necessary to ensure the plastic bezel vent pattern allows air to enter freely so it does not overly restrict airflow into the system.**
- *Rear chassis venting* – This can add to the airflow capability of the chassis, especially to and around the add-in card area.
- *Peripheral bay venting* – Cools peripherals. Minimal venting, if any, should produce adequate results. Implementing too much venting may cause lower airflow in other areas of the chassis.
- *Side chassis venting* – This is not required but may provide airflow to key components depending on the chassis layout.

2.9 Peripheral and Add-in Card Considerations

2.9.1 Peripherals (Hard Drive, DVD, CD-RW)

The general trend for peripheral devices such as 10,000 rpm hard drives, DVD-ROM, DVD-RAM, and CD-RW is an increase in operating temperature and possibly a decrease in the required local ambient temperature necessary for cooling. General power dissipation is around 7 W to10 W and as much as 15 W to 25 W. Operating temperatures are typically 5 °C to 50 °C. Future generations are expected to increase maximum power dissipation and operating temperatures. The system designer must determine the thermal environment of the market segment and ensure that the peripherals are within the published thermal specifications.

2.9.2 Add-in Cards (Graphics Controllers)

The general trend for high performance graphics controllers is toward integrated and higher frequency functions. For competitive 3-D performance levels, the graphics controller power trend will increase over time. The forecasted graphics controller maximum power levels for Accelerated Graphics Port (AGP) introduction are 3-6 W. Future generation graphics controller power is expected to increase to 5-10 W for most controllers, with the potential of up to 15 W for some high performance versions. The system designer must determine the thermal environment of the market segment and ensure that the add-in cards are compatible within this environment.

2.10 Measurement Techniques

2.10.1 Temperature

Temperature can be measured by a diverse array of sensors. These devices all measure temperature by sensing a change in some physical parameter. The six most common types of devices are thermocouples, resistive temperature devices (RTDs and thermistors), infrared sensors, bimetallic devices, liquid expansion devices, and state changing devices. This discussion will focus on three commonly used types: resistive temperature devices, infrared sensors, and thermocouples.

2.10.1.1 RTDs and Thermistors

Resistive temperature devices (specifically thermistors) are commonly used in electronic circuits (such as power supply fan speed control circuits) to sense and control the temperature of electronic components. Resistive temperature devices take advantage of the principle that a material's electrical resistivity varies with changes in temperature. Metallic devices are called *RTD*s, and their resistivity *increases roughly linearly with temperature*. Semiconductor devices are called *thermistors* and their resistivity *decreases nonlinearly with increasing temperature*. Thermistor devices are commonly used in temperature control circuits. Their highly nonlinear behavior poses a problem for circuit designers.

Careful use of matched pairs, such that their nonlinearities offset one another, can minimize this difficulty. Thermistors are usually designated in accordance with their resistance at 25 °C; typical values are around 2 kΩ, 5 kΩ and 10 kΩ.

2.10.1.2 Infrared Sensors

Infrared sensors are non-contacting devices that can be used to provide a thermal map of a system, thus providing an indication of where to place thermocouples for system level testing. Infrared cameras are used to generate these temperature maps within the system during typical operation. These maps indicate which components should be monitored, and instrumented with thermocouples, during thermal validation and qualification testing. Several things affect the accuracy of temperature sensing via infrared devices:

- Materials radiate at various efficiencies due to differences in emissivity.
- Radiation efficiency is affected by localized oxidation, surface roughness, and other factors.
- Infrared energy may be reflected from other sources, rather than the targeted surface.
- The measured surface must completely fill the field of view of the camera.

Infrared sensing devices must account for all these issues to function accurately. To investigate thermal compliance, system components should not exceed their specified thermal limitations during testing. Infrared sensors provide an excellent qualitative indication (thermal map) of system temperatures at various components, i.e., processor, peripherals, add-in cards. If care is taken, these sensors can also provide an accurate quantitative snapshot of overall system temperatures. However, to thermally validate a system, components identified as being near their thermal limits must be instrumented with thermocouples to verify they never exceed their thermal limits under any anticipated loading or environmental conditions.

2.10.1.3 Thermocouples

Thermocouples are the most common temperature sensors used in test and development work. A thermocouple consists of two dissimilar metal wires joined as shown in Figure 2.13. The AB connection is called the junction and is attached at the desired measurement location. The opposite end is the reference end. When $T_{junction}$ is different from $T_{reference}$, a low-level voltage is generated at the terminals. This voltage is quite small and depends on the materials A and B, and $T_{reference}$ and $T_{junction}$. Thermocouples are calibrated in microvolts per degree Celsius.

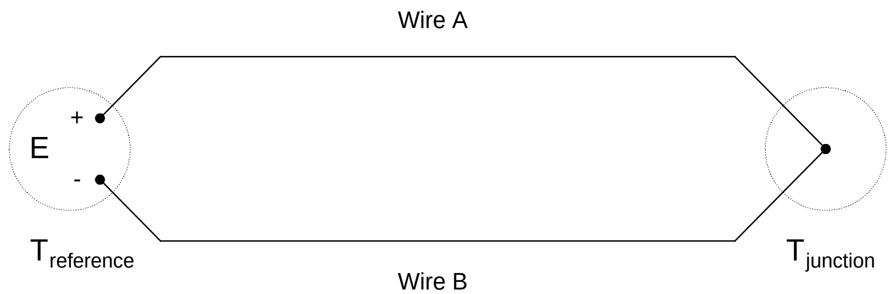

Figure 2.13: A Simple Thermocouple

Care must be exercised when using thermocouples or measurement errors will occur. When attaching a thermocouple to a component, ensure the thermocouple contacts the component completely. Any adhesive or gap between the thermocouple and the component will act as an insulator and the measurements will be lower than the actual component temperature. When placing thermocouples to measure local ambient temperatures, be aware of heat radiating from any high power dissipating components. Shield the thermocouple with aluminum foil or other suitable material to prevent heat radiating to the thermocouple.

2.10.1.4 Thermocouple Types

The three most common types of thermocouple used for measuring moderate temperatures are highlighted in Table 2.3.

Table 2.3: Thermocouple Types

Type	Material	Generated EMF	Temperature Range	Accuracy	Comments
J	Iron-Constantan (white-red wire)	51 µV/°C	0 °C to 750 °C	Standard: 2.2 °C or ¾% Special: 1.1°C or 0.4%	Iron wire is magnetic, susceptible to corrosion and should not get wet; not recommended for low temperature measurements.
K	Chromel-Alumel (yellow-red wire)	40 µV/°C	-200 °C to 1250 °C	Standard: 2.2 °C or ¾% Special: 1.1 °C or 0.4%	Alumel wire is magnetic, susceptible to vibration induced EMF (use strain loops), corrosion resistant.
T	Copper-Constantan (blue-red wire)	40 µV/°C	-200 °C to 350 °C	Standard: 1.1 °C or ¾% Special: 0.5 °C or 0.4%	Not magnetic; wire thermal conductivity is high making it very susceptible to conduction errors; needs large immersion depths.

Table Notes:

1 In the material column, the first named material is the positive element. The second material forms the negative wire, and is color coded red (per U.S. standards).

2 All three types are suitably linear for the ranges of temperature measured in the Intel environmental laboratory. However, Type "J" is typically used to ensure compliance with UL test requirements.

3 The accuracy column can be interpreted as the percent of the difference between $T_{junction}$ and $T_{reference}$. Type "K" thermocouples have a standard accuracy of 2% below 0 °C and Type "T" thermocouples have a standard accuracy of 1.5% below 0 °C.

4 The wires come in a variety of gauges, 30 and 36 being fairly common. The wire should be as small as is practical to prevent heat-sinking of the specimen to the outside world and to prevent disturbance of the air flow, but must be heavy enough to be reasonably durable and resist damage. The recommended wire size for general use in electronic equipment is 30 gauge.

2.10.1.5 Reference Temperature

Transition from thermocouple wires to pairs of copper wire or terminals for connection to measurement circuitry must be done in a controlled constant temperature zone. Since the signal from the thermocouple depends as much on $T_{reference}$ as on $T_{junction}$, it's important to describe this process. The most common ways to set the reference temperature include:

- *Ice baths:* stable, inexpensive and very accurate, but rather inconvenient.
- *Electronically controlled reference sources:* less accurate, more convenient, but requires periodic calibration.
- *Zone boxes:* provide uniform temperature region for connectors, need electronic compensation, most convenient.

Most thermocouple data loggers have the ability to set the reference temperature. Read the instruction manual included with the data logger to understand which method is used.

2.10.2 Airflow

It is essential to understand airflow in order to effect an appropriate thermal management solution. This includes sketching system airflow patterns, and measuring local airflow velocities, system volumetric airflow, and system pressure drops.

- *Airflow patterns:* A simple but effective way to observe system airflow patterns has been to build a clear Plexiglas cover with holes drilled at appropriate locations for inserting smoke probes into the air stream. Insert a smoke probe into the air stream, then observe and sketch the localized airflow pattern. This provides a qualitative assessment of overall system airflow behavior.
- *Localized airflow velocity:* Use a hot-wire anemometer (or similar gauge). These probes provide LFM data perpendicular to the probe head and are highly sensitive to the probe orientation in the air stream. (Note: Probe accuracy is suspect below 30 LFM for most types.)
- *Static pressures:* Insert a static pressure tube perpendicular to the airflow. If the probe is not completely perpendicular to the airflow, the readings will be biased by the dynamic pressure (velocity head) of the air stream. The dynamic and static pressures combine to give the total (or stagnation) pressure.
- *Fan characteristics:* Use an airflow chamber to verify the fan performance curve at various voltages. The chamber can be used to determine the chassis airflow impedance as well.

3. Thermal Test Methodology Example

3.1 Introduction

A designer must make several decisions after the preliminary chassis design is complete and the basic airflow pattern has been established. These include the location and airflow requirements for a system fan (if necessary), selection of a proper power supply, and design of the ducting to direct airflow over key components (if necessary). A designer must next classify and prioritize the design variables for feasibility, cost impact, and ease of implementation.

Once the design variables are prioritized, an experimental design tree can be constructed which outlines all design variable combinations that should be evaluated. An example design tree is shown in Figure 3.1.

This example illustrates two power supply combinations and three different fan speeds. The total number of "runs" required to evaluate this design is determined by counting all the power simulation and airflow boxes at the right edge of the figure. Not all combinations need to be evaluated to determine a robust solution. Some combinations may not be possible due to chassis design, power supply form factor, intended end use, hardware and/or software limitations, or cost implications. This example requires a total of 18 runs to completely evaluate the design.

Next, decide what components will be included in the system design evaluation such as the motherboard, processor type and speed, memory, graphics card (generally AGP), additional add-in cards, and peripherals (CD-ROM, DVD, hard disk drive). **The thermal evaluations performed in this document use current technology (Pentium II processor, 440BX AGPSet, SDRAM, and AGP 2X graphics accelerator) to emulate the technology expected in 1999.** To demonstrate design performance, the system evaluated in this document is configured with the heaviest load the system might encounter in normal use. However, the system designer must decide on an individual basis what the intended use and consequently the thermal load the system under test will experience and configure the system appropriately. Typically all add-in card slots are populated, multiple hard drives are installed, and the highest power processor is used for a heavy load system. If fan speed control is implemented on either the power supply or system fan, the system should also be evaluated with combinations of light and heavy loads and high and low temperature.

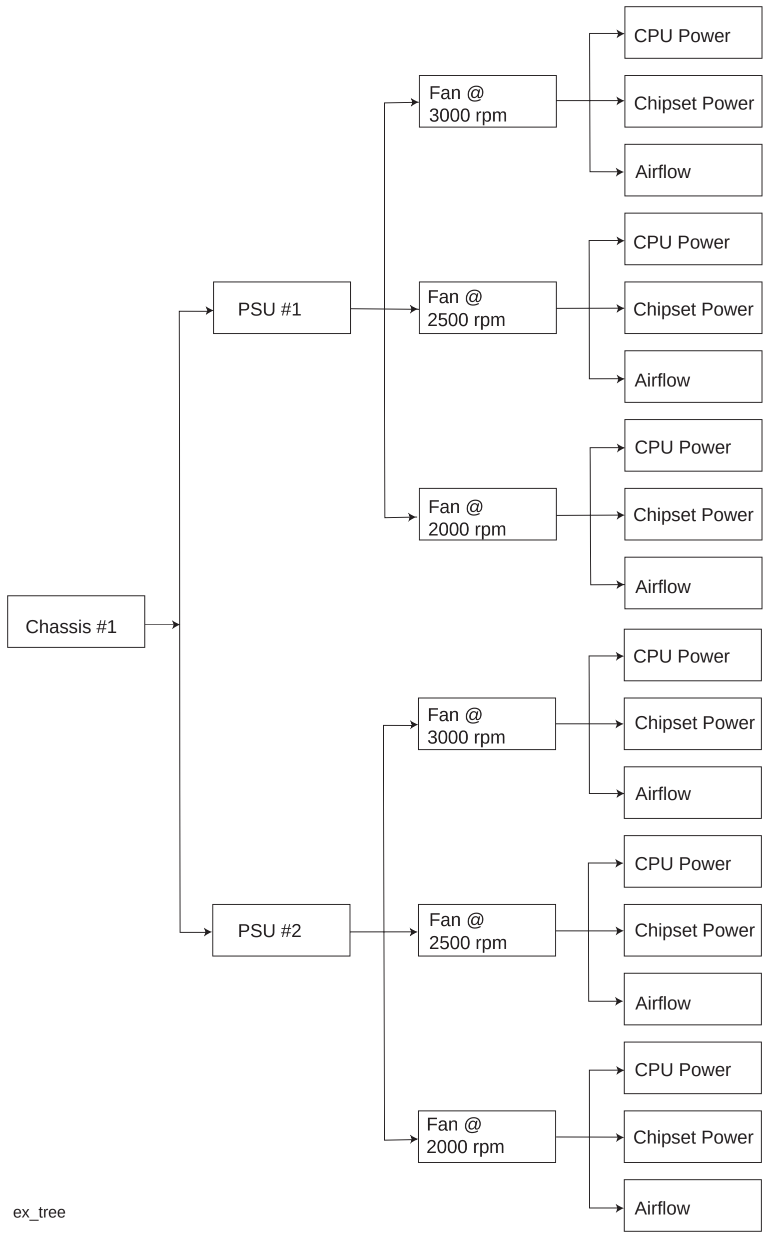

Figure 3.1: Experimental Design Tree

Different software programs tax the system components at power levels varying from the minimum to the maximum published power. Thermal design performance should be demonstrated at the maximum power dissipation of all components. Power simulation software serves this purpose. These software utilities emulate the anticipated maximum power dissipation of the processor, chipset, memory, and AGP graphics accelerator. While it is impossible to emulate the maximum power dissipation of all components at the same time, simulating the maximum power of each component separately ensures unanticipated failures will not occur in the field later.

Common temperature and airflow measurement techniques should be used to collect the pertinent data for the key system components. Typical testing includes both thermocouple and hot-wire anemometer probe use to ensure key components do not exceed the published specifications for the maximum temperature.

Depending on the design, system temperatures may not stabilize for over one hour when executing power simulation software. Therefore, robust data acquisition techniques are often necessary to monitor temperature variation over time. Data acquisition equipment with the ability to monitor multiple thermocouples simultaneously and interfaced to a personal computer is highly recommended. The multiple channel capability allows the designer to monitor temperature fluctuations versus time at any location in the system. The personal computer interface provides automated data collection at predetermined time intervals to easily monitor the fluctuations and determine when temperatures have stabilized.

After data collection is complete, each design variable combination should be evaluated for thermal performance, feasibility, ease of implementation, and cost impact. Often, the lowest component temperature design has associated feasibility or cost drawbacks making the best solution a compromise among all factors.

3.2 Definitions

- **Light Load –** Basic system configuration with processor, one hard drive, and one CD-ROM drive. No add-in cards or secondary hard drives are installed.
- **Heavy Load –** Basic system configuration with all add-in card and peripheral bays populated. Some assumptions must be made for the power dissipation of the add-in cards and peripherals. Maximum add-in card and peripheral power dissipation is typically set at 10 W each.
- **Low Temperature –** Room ambient (22 °C) (sea level)
- **High Temperature –** 35 °C (sea level)
- **Four-corner thermal testing –** Testing at both heavy and light load, and high and low temperature. Combinations are:
  - Low temperature and light system load
  - Low temperature and heavy system load
  - High temperature and light system load
  - High temperature and heavy system load

3.3 Data Acquisition Techniques

Some type of apparatus must be used to measure the temperature of each thermocouple. If very few thermocouples need to be monitored, handheld devices and manual tracking at specified intervals can be used to determine when the temperatures stabilize. However, data collection becomes very difficult, time intensive and error prone with numerous thermocouples.

For system level evaluation where many thermocouples are required, the data acquisition technique should be automated to eliminate errors associated with manual data collection. This also makes temperature tracking and system temperature stabilization easier to determine.

Key benefits of automated data acquisition are:

- Multiple thermocouple monitoring capability. Twenty channels should be the minimum monitoring capacity.
- The unit can export collected temperatures through a serial I/O port to the computer for analysis.
- Through software, the temperature of each thermocouple over time may be displayed graphically making temperature stabilization easily identifiable.
- Data can be stored in spreadsheet format for additional data analysis and record keeping.

Many units that have these capabilities are available, such as Hewlett Packard Data Acquisition/Switch Unit Model 34970A or the Fluke Hydra Data Logger.

The steps required to collect the thermal data are listed below.

1. Determine desired system configuration: chassis, motherboard, processor, hard drives, CD-ROMs, add-in cards, and other components.
2. Determine pertinent cooling components: power supply, system fan (if used), processor active or passive heat sink, and ducting.
3. Place thermocouples on the components and key locations.
4. Boot the computer and verify proper operation.
5. Execute the power simulation software for individual components.
6. Collect temperatures with the data acquisition unit.
7. Monitor temperatures using software interface until temperatures stabilize. Depending on system design, temperatures may require up to two hours to stabilize.
8. Stop power simulation software and repeat the procedure for other power simulation software.

Airflow data acquisition is similar; however, power simulation software is not executed and a minimum ten minute stabilization period is required before data is collected.

3.4 Key Integrated Circuit Devices

3.4.1 Pentium® II Processor

Guidelines have been established for the proper techniques to be used to ensure the Pentium II processor is within thermal specification limits. Data sheets *Intel® Pentium® II Processor* and *Intel® Celeron™ Processor* provide information on how to accurately measure temperatures and how to run the power simulation software that will emulate the anticipated maximum thermal design power.

3.4.2 Chipset

Guidelines have been established for the proper techniques to be used when measuring the chipset case temperatures. The *82443BX PCISet Application Note* provides information on how to accurately measure the case temperature, and run the power simulation software which will emulate the anticipated maximum thermal design power.

3.4.3 RIMM: RDRAM In-line Memory Modules

Typically case or junction temperatures are measured to determine component thermal compliance. The initial RDRAM thermal specification presently requires local ambient temperatures and local airflow measurements to determine thermal compliance. These local measurements are used to determine the corresponding junction temperature for RDRAM with heat spreaders dissipating 6 W, per Figure 3.2 (max spec 100 °C)[3]. Manufacturers are expected to supply RIMM case temperature specifications when the memory becomes available.

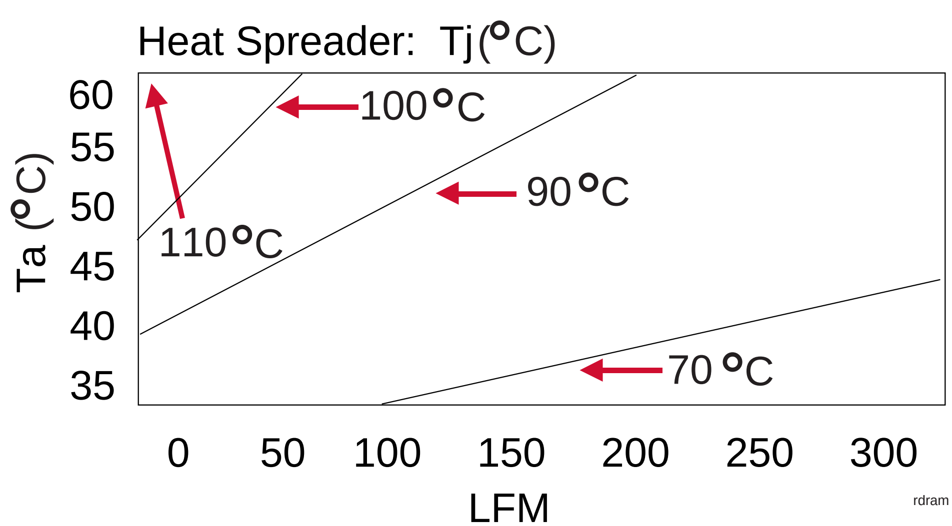

Figure 3.2: RDRAM Junction Temperature

[3] Specification as of September 1998.

3.5 ATX System Configuration

The ATX motherboard size (12 in x 9.6 in maximum) is fairly standard across the industry. Intel currently manufactures several ATX motherboards for performance platforms. The SE440BX motherboard was used for system thermal testing.

Two ATX form factor chassis combined with three different power supplies are evaluated. The first chassis is a mid-tower unit and the second unit is a mini-tower. The mid-tower locates the power supply in the top rear of the chassis whereas the mini-tower has the power supply located over the processor, chipset, and memory. For all evaluations, the power supply is configured to evacuate the chassis with the fan operating at 12 VDC.

Thermal design performance should be demonstrated with the heaviest load the system might encounter in normal use. All available add-in card slots and peripheral bays are populated. Add-in cards vary widely in power dissipation and temperature requirements so resistive load cards designed to dissipate a user adjustable heat load are used to simulate typical add-in cards. SCSI and IDE hard disk drives, and IDE CD ROM drives populate all available drive bays. The typical heavy system configuration is listed in Table 3.1.

Table 3.1: System Configuration

Component	**Type**	**Chassis Quantity**	
		Mid-tower	Mini-tower
Motherboard	Intel SE440BX	1	1
Processor	Pentium II processor, 300 MHz	1	1
Memory	128 MB, 100 MHz SDRAM	3	3
Graphics – Add-in card	Intel740™ chip based AGP	1	1
PCI	10 Watt Resistive Load Card	4	4
ISA	10 Watt Resistive Load Card	1	1
Floppy Drive	Standard	1	1
Primary Hard Drive	IDE, 3600 rpm	1	1
Secondary Hard Drives	SCSI (idle), 7200 rpm	2	2
CD-ROM	IDE CD-ROM	2	2
Power Supply[1]	PSU 1 PSU 2 PSU 3	1 1 1	1 1

Note 1. PSU 1, 2, 3 are discussed in Section 4.5.

3.6 Power Dissipation

The processor, chipset, memory, and graphics are the major contributors to the thermal load on the system. The power dissipation and temperature specifications for the components used in the evaluations are listed in Table 3.2.

Table 3.2: Power Dissipation

Component	Thermal Design Power (Reference Only)	Temperature Spec (Reference Only)
Pentium® II processor, 300 MHz	41.4 W	72 °C
SDRAM	6 W	Not Applicable for RDRAM Simulation
82443BX Host Bridge/ Controller (PAC)	4 W	105 °C
Graphics (AGP 2X)	6 W	109 °C (Intel740 chip)
Add-in Cards	-	T_{amb}<55 °C
Peripherals	-	T_{case}<55 °C

Note: Specifications as of September 1998.

Please refer to the Application Notes for the corresponding components to obtain the published thermal design power and maximum temperature specifications. The next generation processor, chipset, and RDRAM memory are not currently available for evaluation. Each of these components is simulated using current technology. The Pentium II processor operating at 300 MHz simulates the next generation processor, the 82440BX chipset simulates the new chipset, and SDRAM memory physically simulates the RDRAM memory.

The next generation processor is not expected to exceed the maximum power dissipation of the Pentium II processor. Future testing with the next generation processor is needed to evaluate its true thermal performance. The next generation chipset specifications are not available currently; however, the heat transfer mechanisms remain the same so the 82440BX chipset is used for approximate power simulation. SDRAM dissipates approximately the same power as RDRAM even though the temperature specifications differ. SDRAM specifies case temperatures whereas RDRAM specifies local ambient temperatures and airflow velocities. For RDRAM simulation purposes, the local ambient temperatures and airflow velocities are measured instead of the SDRAM case temperature.

Add-in cards and peripherals vary significantly in power dissipation. The manufacturer's specifications should be consulted for the thermal design power and maximum temperature specifications.

3.7 Power Simulation Software

Power simulation software includes utilities specifically written to test the thermal design power for Pentium II processors, the 82440BX chipset, and Intel740 chip based AGP graphics cards. This software is used to monitor the thermal performance under "worst-case" system component conditions. Future applications may exceed the thermal design power limit for transient or all time periods. **Power simulation software is intended to simulate "worst-case" conditions but does not guarantee thermal compliance for future software applications.**

The processor is exercised using the utility KPOWER.exe. The exact power dissipation of the processor while executing KPOWER.exe is unknown but estimated at 80% of the published processor power.

The chipset is exercised using the utility BTTS01.exe. The power dissipated with BTTS01.exe depends on which switches are activated. The "/u2" option is most commonly used and will dissipate between 6.5 W and 7 W depending on the number of DIMM slots populated.

The Intel740 graphics accelerator maximum thermal design power was simulated using the software utility THERM740.exe. The exact power dissipation is unknown but is approximately 6 W.

Power simulation software for future processors, chipsets, and graphics accelerators may change. Ensure the correct simulation software is used for the component in question.

Please contact your local Intel representative for more information about the power simulation programs.

3.8 Thermocouple Placement and Type

Key components and additional thermal points of interest were monitored for each desired cooling configuration in each chassis. Type J, 30 gauge thermocouples are used at these locations. Please refer to the Intel Pentium® II Processor data sheet for thermocouple attachment procedures. Thermocouple locations are listed in Table 3.3 and shown in Figure 3.3 for the mini-tower chassis only. Locations are similar in the mid-tower chassis.

Table 3.3: Thermocouple Locations

Name	Location	Number
Processor	Processor plate temperature, center of thermal plate	T1
82443BX controller	Case temperature, center of chip	T2
Memory Ambient – Top	0.1-0.2” above top of memory toward top of chassis	T3
Memory Ambient – Bottom	0.1-0.2” above top of memory toward bottom of chassis	T4
Memory Exit – Top	0.1” above motherboard toward top of chassis	T5
Memory Exit – Bottom	0.1” above motherboard toward bottom of chassis	T6
Add-In Card Ambient – Rear	0.75”-1” above add-in cards towards back of chassis	T7
Add-In Card Internal Ambient	½ way from motherboard centered between add-in cards	T8
Add-In Card Ambient – Middle	0.75”-1” above add-in cards towards middle of chassis	T9
Add-In Card Ambient – Front	0.75”-1” above add-in cards towards front of chassis	T10
Hard Drive Case	On top of primary hard drive case	T11
CD-ROM	On top of lower CD-ROM case	T12
CD-ROM	On top of upper CD-ROM case	T13
External Power Supply	0.5”-1” in front of power supply air outlet on outside of chassis	T14
LPFD Vent (when required)	0.5”-1” in front of LPFD vent	T15
Internal Power Supply	0.25-0.5” in front of internal power supply air inlet inside chassis	T16
AGP chip case	Controller case temperature, center of chip	T17
AGP board	Backside of board in center of chip	T18
Processor Local	0.25” above center of heat sink	T19
82443BX Local	0.25” above center of controller case	T20
Ambient	External and away from chassis	T21

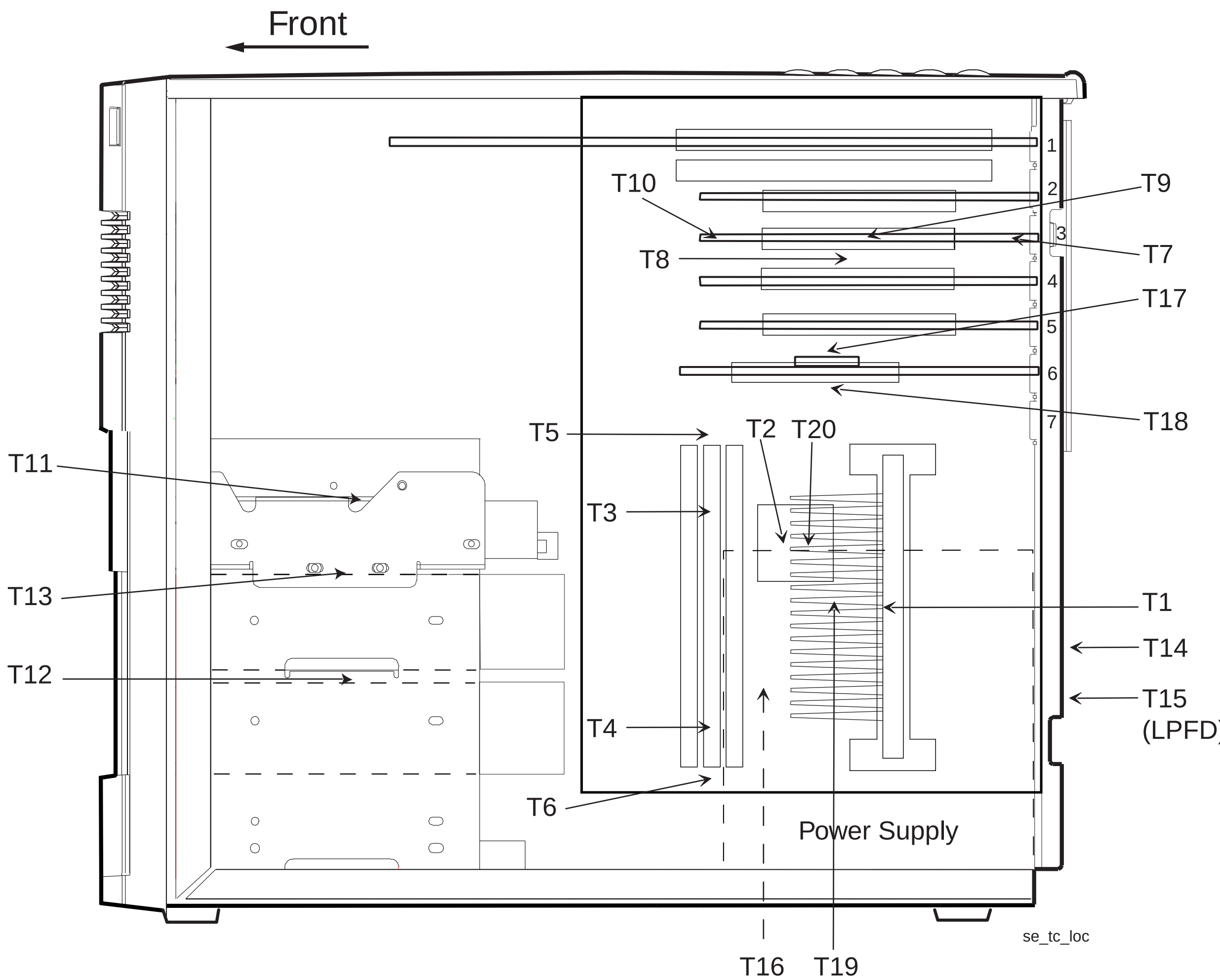

Figure 3.3: Thermocouple Locations in ATX Mini-Tower System

3.9 Airflow Sensor Placement and Type

Key airflow pathways of interest are monitored for each desired cooling configuration in each chassis. Cambridge Accusense flow sensors (hot wire anemometer) are used at these locations. Probe locations are listed in Table 3.4 and shown in Figure 3.4 for the mini-tower chassis only. Locations are similar in the mid-tower chassis.

Table 3.4: Airflow Sensor Locations

Name	Location	Flow Velocity Direction	Number
Processor	Top of heat sink, near top of chassis	Y	A1
Processor	Top of heat sink, near bottom of chassis	Y	A2
Processor	Bottom of heat sink, near top of chassis	Y	A3
Processor	Bottom of heat sink, near bottom of chassis	Y	A4
Memory	In front of DIMM 0, parallel to memory, in center of memory card	Z	A5
Memory	In front of DIMM 0, in center of memory card	Y	A6
Memory	Behind DIMM 2, in center of memory card	Z	A7
Memory	Behind DIMM 2, in center of memory card	Y	A8
Memory	Between DIMM 0 and DIMM 1 near bottom of chassis as close to motherboard as possible	Z	A9
Memory	Between DIMM 0 and DIMM 1 near top of chassis as close to motherboard as possible	Z	A10
Chipset	0.2” above chipset	Y	A11
LPFD Inlet-top	Behind LPFD inlet vent, top side of vent	X	A12
LPFD Inlet-center	Behind LPFD inlet vent, center of vent	X	A13
LPFD Inlet-bottom	Behind LPFD inlet vent, bottom side of vent	X	A14
Power Supply	In front of internal power supply vent	Y	A15
Power Supply	In front of external power supply vent	X	A16
AGP	AGP processor chip	Y	A17
AGP	AGP airflow on backside of card	Y	A18

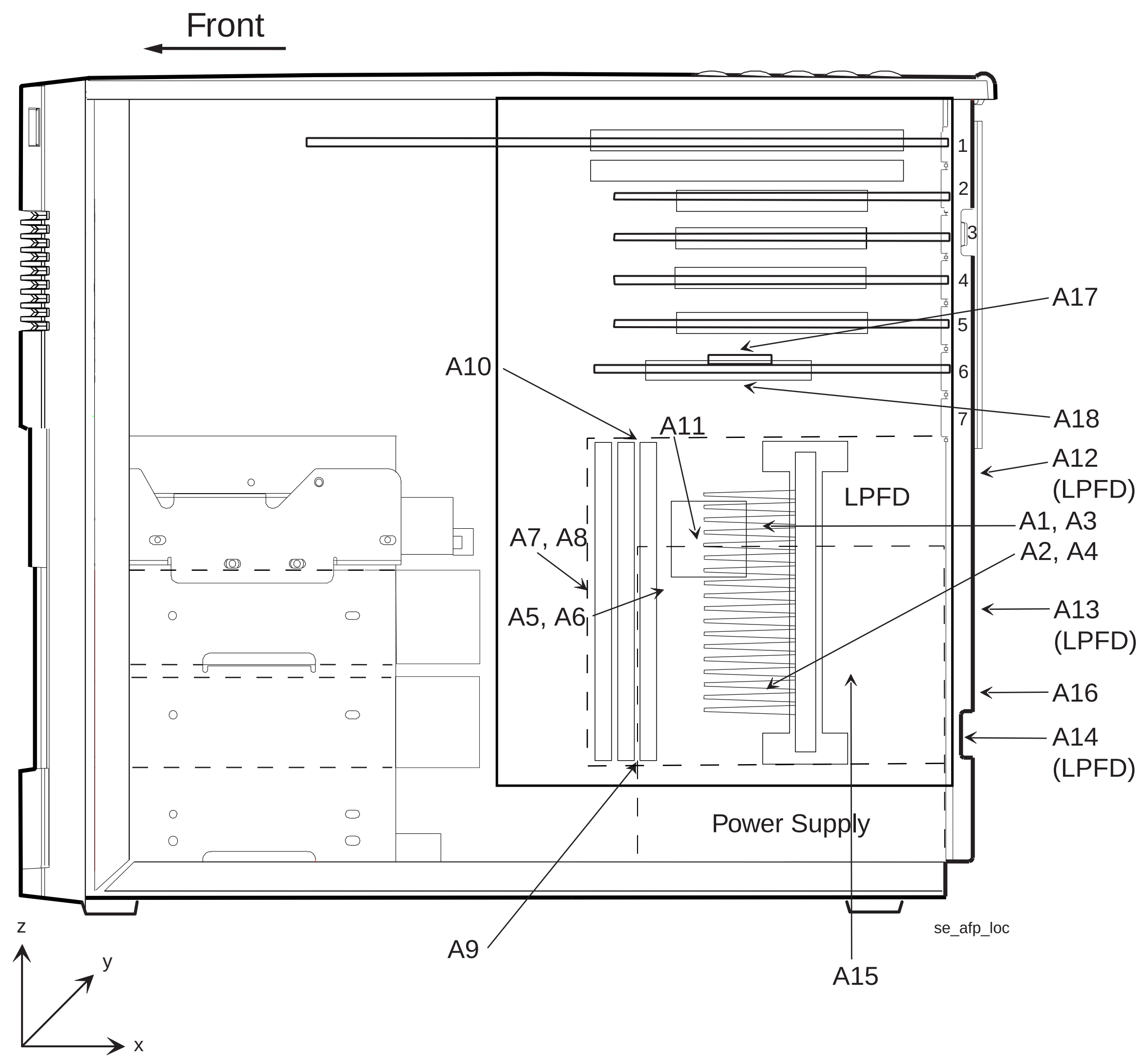

Figure 3.4: Airflow Sensor Locations in ATX Mini-Tower System

4. System Design Examples

4.1 Introduction

The ATX form factor system design examples focus on the mini-tower (Figure 4.1) and the mid-tower (Figure 4.2) chassis.

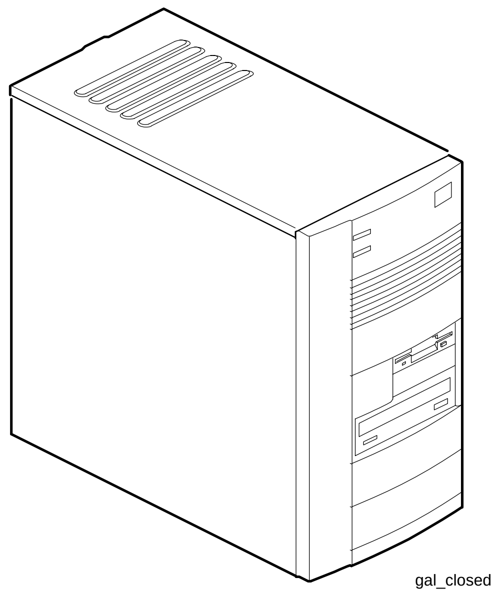

Figure 4.1: Mini-Tower Chassis

These two chassis are representative of typical commercially available designs. These two are chosen to compare the top rear and mid-mount power supply locations. As described in Section 2.8.2, the mid-tower chassis locates the power supply in the top rear corner whereas the mini-tower chassis locates the supply over the core logic components. **Inclusion in this document should not be construed as a recommendation or disapproval of the particular chassis or chassis design.**

The power supply is among the most influential components in the cooling system design. Proper selection is critical to meeting the maximum specified component temperatures. Because of this importance, three different power supplies are used in the evaluation process to demonstrate their affect. In all cases, the power supplies are configured to evacuate the chassis with the fan operating at 12 VDC. The mid-tower chassis is evaluated in the “as received” configuration to establish a baseline cooling capacity. This standard configuration includes a power supply not chosen for evaluations. However, this power supply is listed for reference only.

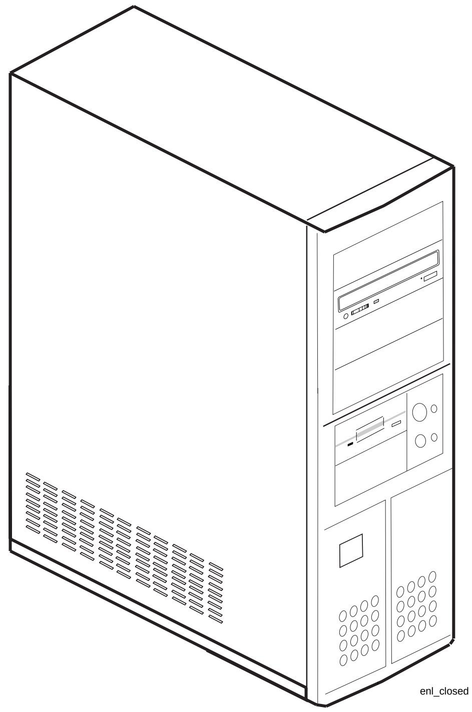

Figure 4.2: Mid-Tower Chassis

Vent sizes, locations, and bezel design can dramatically affect the system airflow patterns. Placing the vents in the proper locations can reduce component temperatures to satisfactory levels that were previously above the maximum temperature specification. Add-in cards and peripherals prove to be especially sensitive to this affect. As such, vent sizes and locations are investigated in the evaluation of the mid-tower chassis.

Based on the typical ATX chassis flow pattern described in Section 2.8, the design process started with a brainstorming session for ideas to cool the processor, chipset, memory, and AGP graphics card. Considering feasibility, ease of implementation, and cost the ideas are reduced to three possibilities.

- Place an active fan heat sink on the processor.
- Install the Horizontal Fan Heat Sink (HFHS)
- Install the Low profile fan Duct (LPFD)

4.2 Processor Active Fan Heat Sink

The active fan heat sink on the processor is considered because of the need for a “boxed product” solution that can be purchased separately. The active fan heat sink is a chassis independent solution allowing it to be implemented across all form factors. However, the active fan heat sink (Figure 4.3) is intended to cool only the processor and not the chipset, memory, or AGP graphics card. If the airflow patterns established by the power supply and the chassis layout are adequate to cool the other key components, the active fan heat sink for the processor may be feasible thermally.

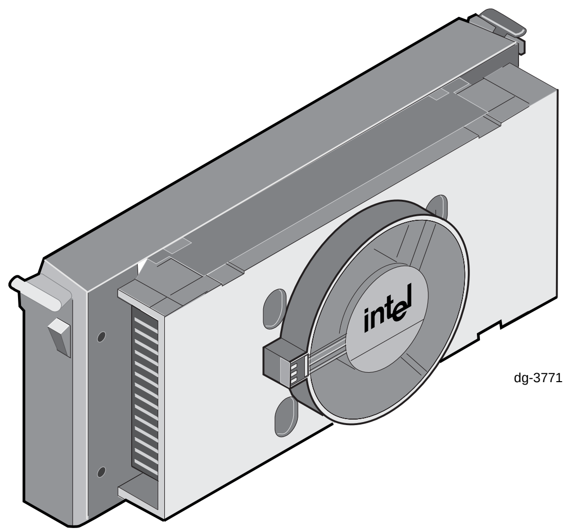

Figure 4.3: Active Fan Heat Sink

Numerous processor active fan heat sinks are available commercially. The unit used for this evaluation is the Sanyo Denki model 109X1512H3036 rated at 12 VDC at 0.06 A. The fan on the unit averages 4200 rpm under normal operating conditions. For proper processor cooling, the ambient inlet temperature of the fan heat sink must not exceed 45 °C.

No system fans were installed other than the power supply fan for all configurations.

4.3 Horizontal Fan Heat Sink (HFHS)

The HFHS (Figure 4.4) is a standardized fan heat sink technology designed for ATX, microATX, and NLX systems. The cooling concept is similar to the active fan heat sink but uses an 80 mm fan to increase the airflow to the processor, adjacent chipset component, and memory whereas the active fan heat sink increases airflow to the processor only.

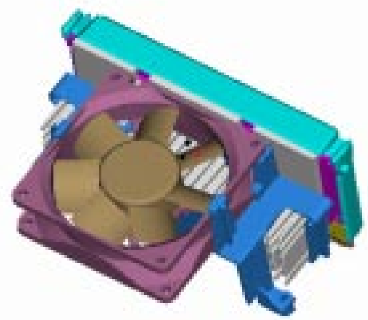

Figure 4.4: Horizontal Fan Heat Sink

Key advantages of the Horizontal Fan Heat Sink include:

- The HFHS is chassis independent and therefore one design usually fits for all form factors (ATX, microATX, NLX).
- The 80 mm fan is located directly above the processor, adjacent chipset component, and memory, increasing the cooling benefit of this system fan.

Key disadvantages:

- The fan is cantilevered off the processor, adding mass, which can affect shock and vibration responses for the processor package.
- Internal ambient air temperatures must be well managed because HFHS recirculates internal air rather than utilizing cool external air.
- A custom processor heat sink is required for this approach because the fan is inset into the heat sink.

All ATX chassis evaluations using the HFHS are performed with a prototype fan bracket mounted to an SECC style processor, and an ATX heat sink modified to accept a 3200 rpm, 80 mm fan installed in the HFHS bracket. Two system fans unnecessarily add cost; therefore the front system fan is never installed in either the mid-tower or mini-tower chassis.

HFHS is a conceptual design and limited prototypes have been manufactured for thermal evaluation purposes only. Critical design issues concerning the bracket such as processor and/or motherboard attachment points must be addressed if an HFHS is adopted. Processor packaging style such as SECC vs. socketed must also be considered. If this design or a similar design is adopted, evaluation by the system designer is highly recommended to demonstrate both thermal and mechanical design performance.

When properly implemented HFHS is capable of effectively cooling all key system components, add-in cards, and peripherals in each chassis. However, fan speed control or a

slower HFHS fan could possibly be implemented if proven thermally viable with further investigation.

4.4 Low Profile Fan Duct (LPFD)

The LPFD concept allows the designer to mount a fan over the core logic components including the processor, chipset, and memory. The concept employs a duct (Figure 4.5 and Figure 4.6) that enables the fan to draw in fresh air from the outside and spread it around the entire core of the system.

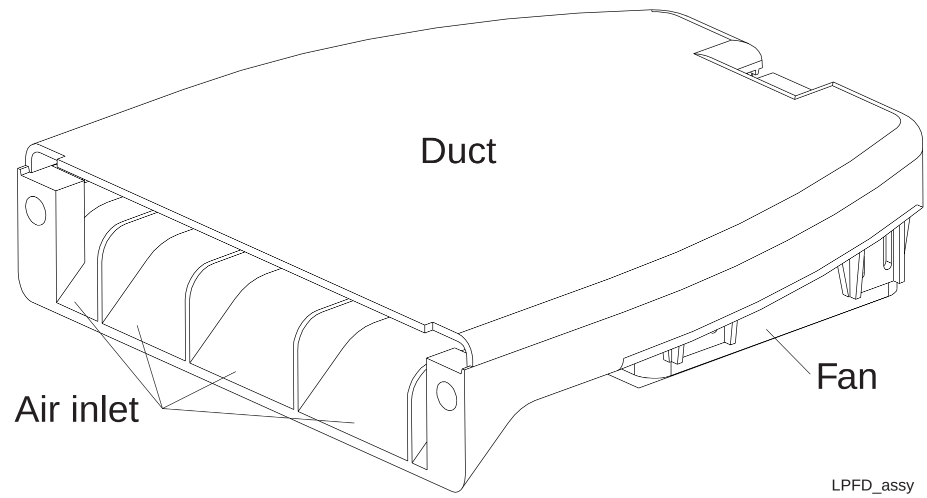

Figure 4.5: Low Profile Fan Duct Assembly

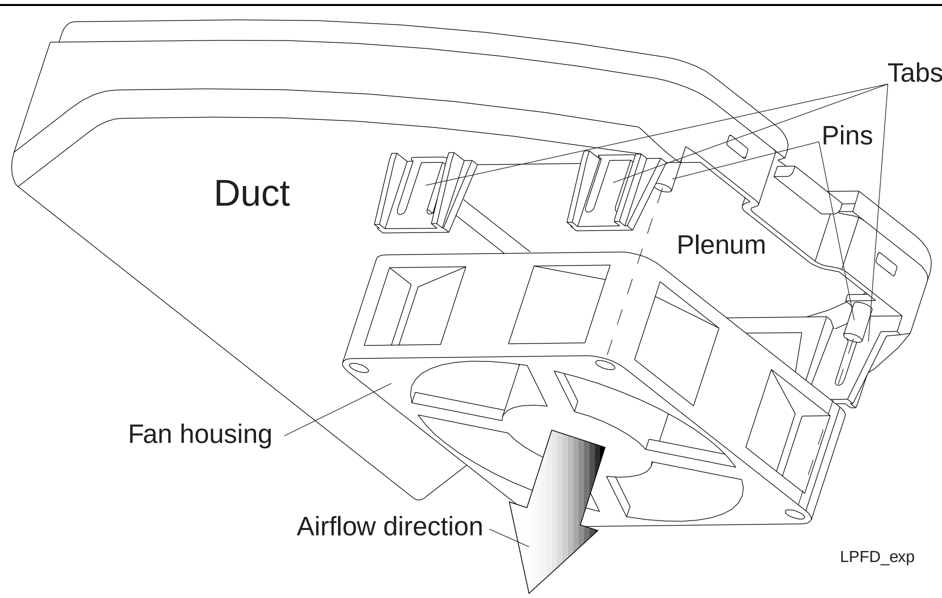

Figure 4.6: LPFD Assembly, Exploded View

Key advantages of the LPFD include:

- Delivery of cool external air to the core logic components.
- The fan is located directly above the processor, chipset, and memory, increasing the cooling benefit of the LPFD fan as illustrated in Figure 4.7.
- Possible to conform to the ATX/microATX motherboard specifications, making it motherboard independent.

Key disadvantages:

- The duct attaches to the rear wall of the chassis and optionally to the motherboard possibly requiring “keep-out” areas on the motherboard as shown in Figure 4.7.
- An inlet for the duct is required in the rear panel as illustrated in Figure 4.8 in the mini-tower chassis.
- A custom processor heat sink is required because the fan is inset into the heat sink.

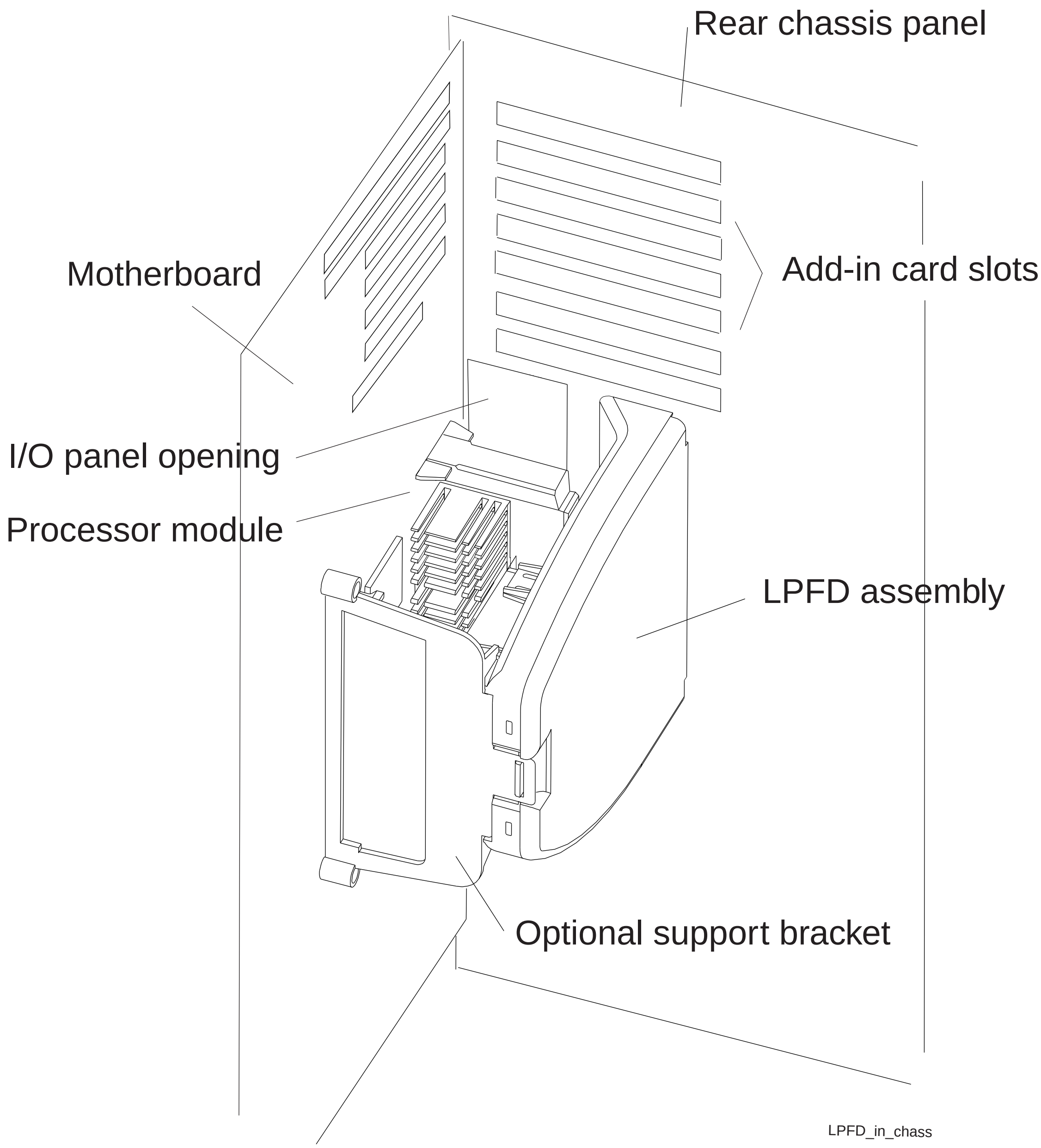

Figure 4.7: LPFD Assembly, Installed

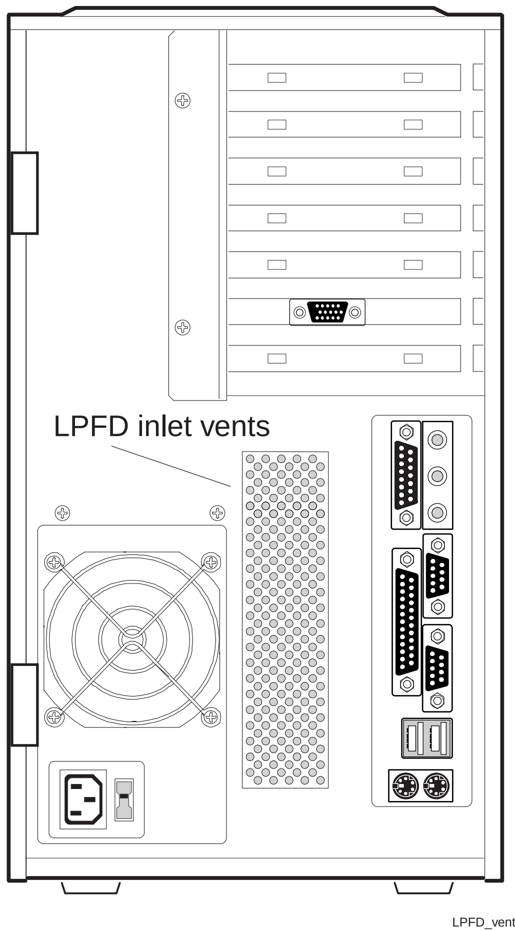

Figure 4.8: Inlet Vents for LPFD

Figures 4.5 through Figure 4.7 depict a completed reference design implementing the design information found in the LPFD specifications. See the “Low Profile Fan Duct Motherboard and Chassis Specification”, the “Low Profile Fan Duct System Ingredients Specification”, and the “Low Profile Fan Duct Design Guidelines” located at http://developer.intel.com/ial/sdt/fanduct.htm for additional information and requirements when designing the LPFD. Evaluation by the customer is highly recommended to demonstrate both thermal and mechanical performance of LPFD in their system.

Two early prototype fan duct systems (prior to the reference design) were characterized in various ATX chassis configurations, see Section 4.7 for additional details and test results from these prototype systems. In Section 4.7, two fan duct prototypes were evaluated, designated ‘small’ and ‘large’. The ‘small’ fan duct has duct inlet dimensions of 0.625 in x 5 in and the ‘large’ fan duct inlet is 1.25 in x 5.165 in, see Section 4.7 for more details.

4.5 Power Supply

The power supply is among the most influential components in the cooling system design as mentioned in Section 2.5. This is especially true with the chassis and cooling methods evaluated. Because of the heavy power supply dependence, three different supplies are implemented in the combinations to illustrate their significant effect.

The vent sizes and locations, and fan flow rate, differentiate each power supply chosen for the evaluations. The supplies are depicted in Figure 4.9 through Figure 4.11.

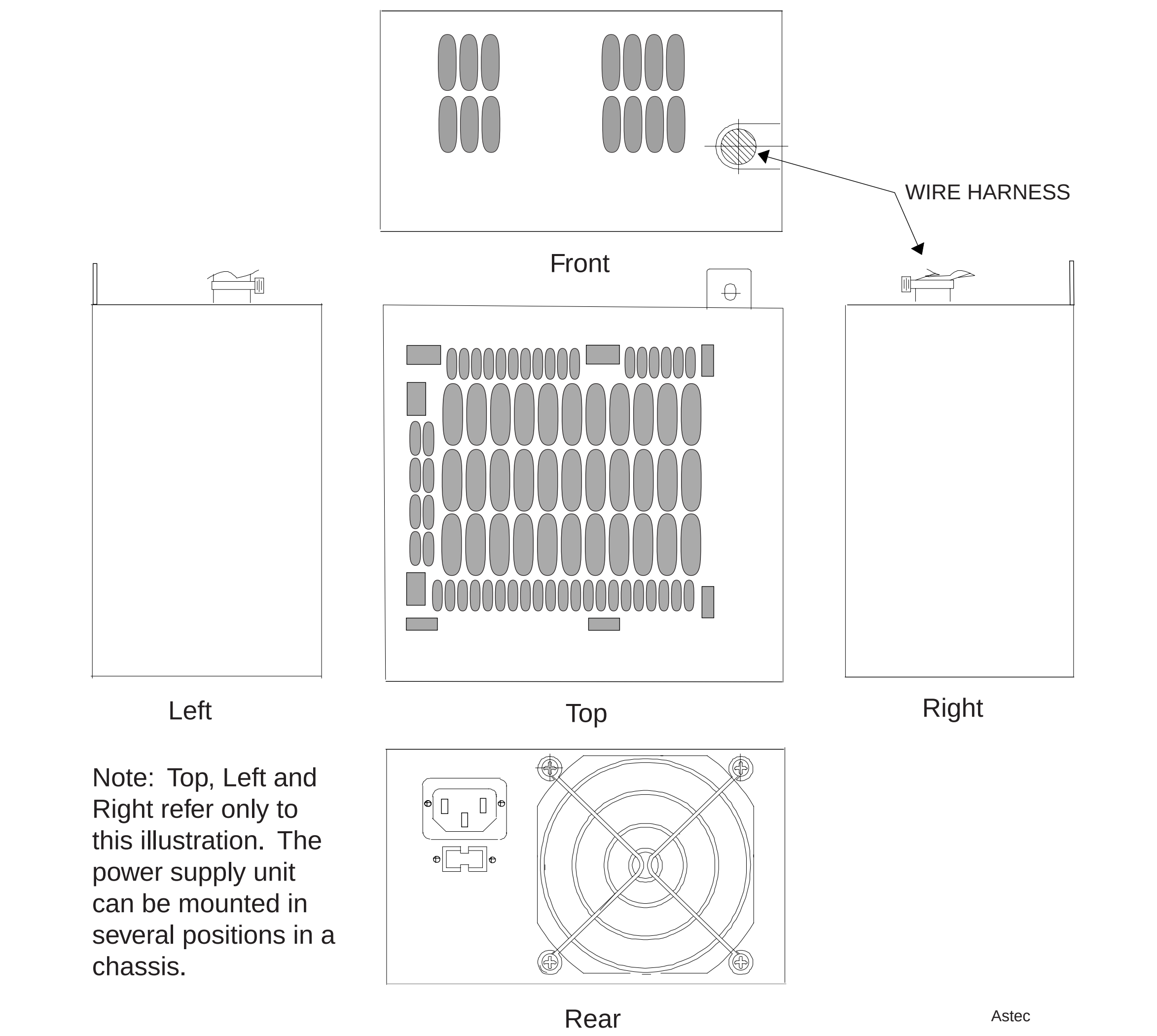

Figure 4.9: Power Supply 1

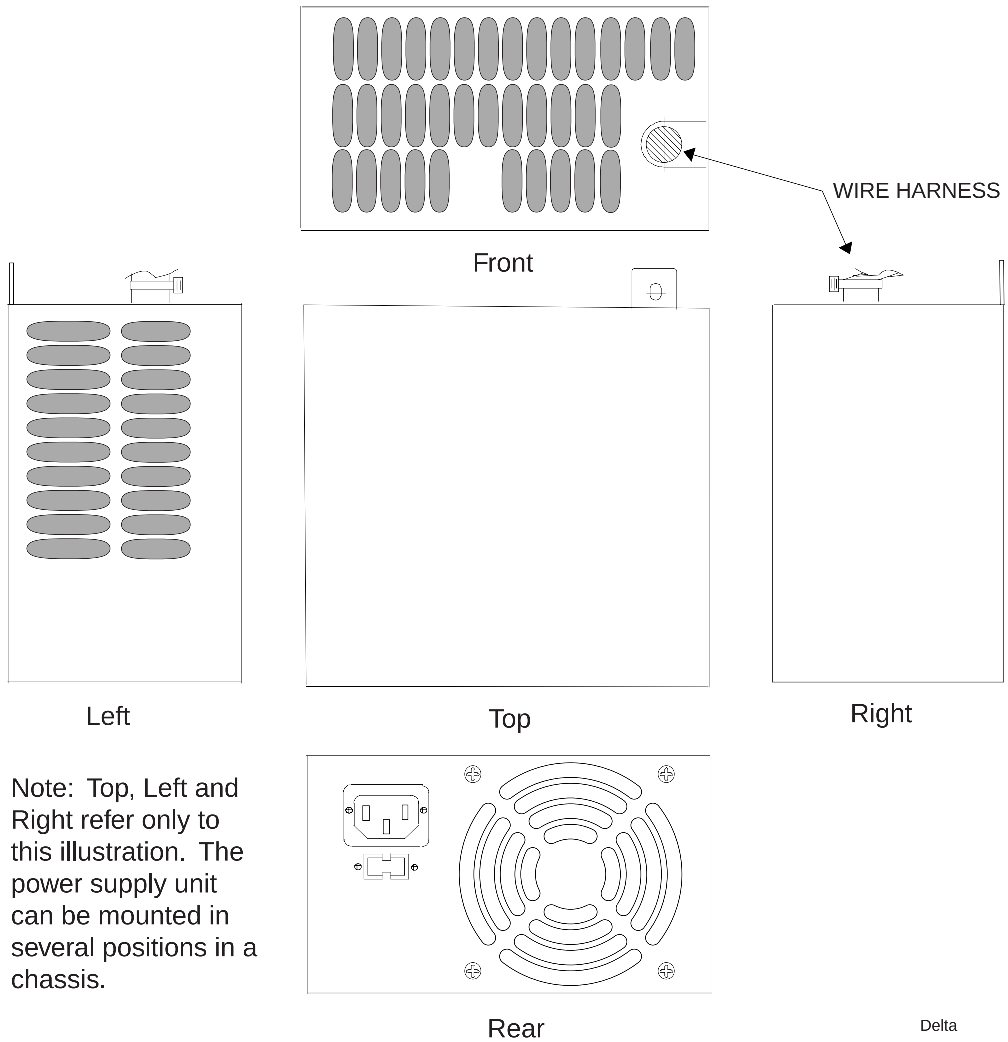

Figure 4.10: Power Supply 2

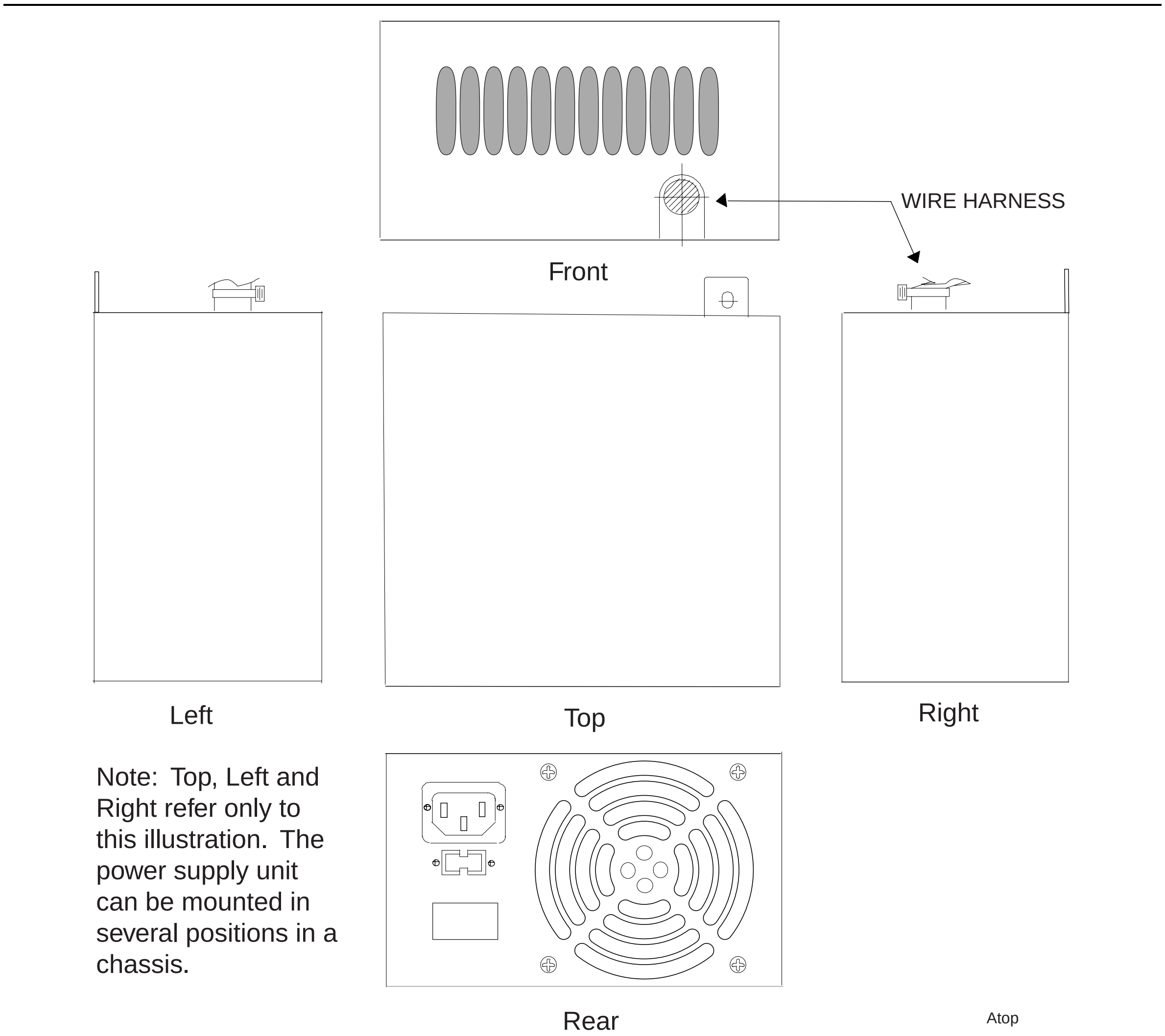

Figure 4.11: Power Supply 3

Each power supply utilizes an 80 mm fan to create flow through the unit. However, the fans do not operate at the same speed and the vent size and locations are different for each supply (as illustrated in Figures 4.9 through 4.11). Therefore, the volumetric flow rate varies between supplies. Table 4.1 compares the volumetric airflow of each power supply.

Table 4.1: Power Supply Volumetric Airflow

Power Supply	Fan Speed (rpm)	Fan Voltage (VDC)	Volumetric Airflow (cfm)
PSU 1	3100	12	~20
PSU 2	3000	12	~16
PSU 3	2200	12	~9

Notes:

Volumetric airflow stated is for the supply only.

System volumetric airflow will be lower due to increased impedance.

Figure 2.7 depicts the power supply characteristic curves for these three units that determine the volumetric airflow shown in Table 4.1. Inspecting the venting in the above figures explains the difference in the flow rates between the supplies. PSU 1 has very liberal venting on the top face with additional venting on the front face. Also note the wire fan grille instead of a stamped sheet metal style grille. PSU 2 has large vents on the front face and left side whereas PSU 3 has a similar pattern to PSU 2 on the front face but the vent is much smaller and there is no venting on the other sides.

4.6 Chassis Venting

Proper chassis venting achieves the low impedance required for high system airflow with smaller power supplies. Location of these vents serves the important role of distributing the air to the components of interest.

Add-in cards and peripherals tend to be especially sensitive to vent size and location. If the vents are not located properly, the add-in cards will not be in the airflow path and thus will be relegated to a natural convection environment. Even if the vent is located properly, size must be considered. When the vent is too small, the chassis impedance increases and thus restricts the total flow through the system. If the vent is too large, the total airflow will be adequate but the local add-in card velocity will be very low, once again creating the natural convection environment.

Because of the significant affect vent size and location has on add-in card cooling, the mid-tower chassis vent scheme is investigated to determine if add-in card temperatures could be improved. As such, the side vent is relocated further rearward and lower to the base of the chassis as depicted in Figure 4.12 and Figure 4.13. In addition the suggested vent is taller (3.5 in vs. 2.5 in) but narrower (6.25 in vs. 10.5 in). This should increase the velocity across the add-in cards and thus create a forced convection environment yet maintain high volumetric airflow through the system.

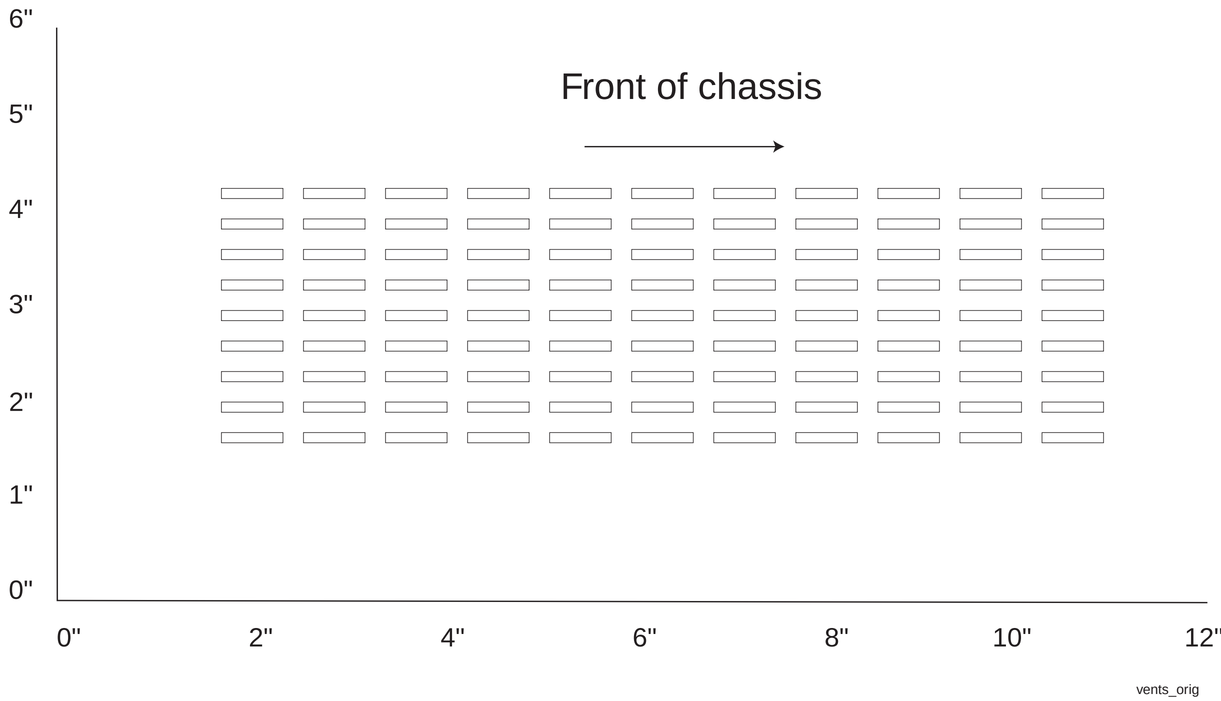

Figure 4.12: Standard Vent Location

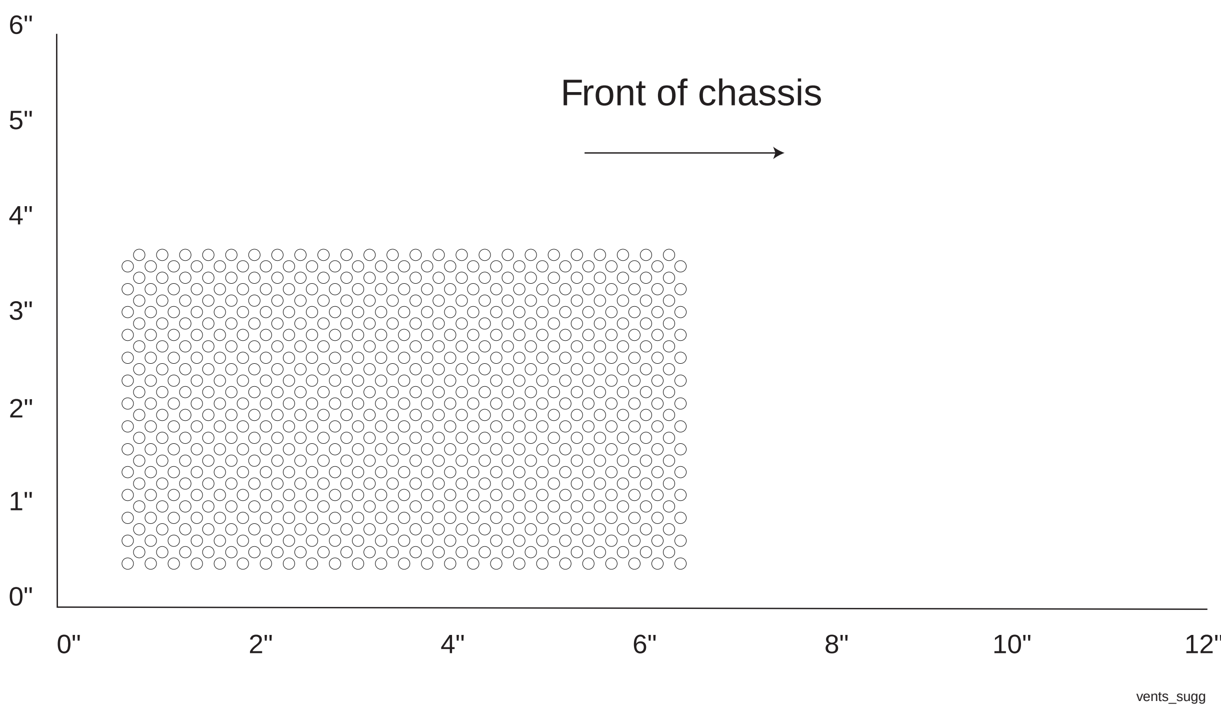

Figure 4.13: Suggested Vent Location

4.7 Results

The overall system thermal design must cool five critical components below the maximum specified temperature listed in Table 3.2.

- Processor thermal plate temperature
- Case temperature of chipset device that requires cooling
- RDRAM local ambient temperature and airflow velocity
- AGP controller case temperature
- Add-in card local ambient temperature and peripheral temperatures

The active processor fan heat sink, HFHS, and LPFD are evaluated against the maximum temperature specifications in the mid-tower and mini-tower chassis. For each cooling method, recommendations and conclusions are discussed to refine the thermal design.

4.7.1 Mid-Tower Chassis

Table 4.2 compares the cooling methods proposed. In Table 4.2 all temperatures are extrapolated to 35 °C ambient air temperature; all temperatures are in °C; all velocities are in linear feet/minute (lfm). The “as received” configuration is evaluated to establish a baseline for the chassis and is intended for reference only. This configuration is considered a heavy loaded system.

Table 4.2: Mid-Tower Chassis (Heavy Load)

Cooling Method	Power Supply	Vent Pattern[1]	CPU Tplate[2]	82443BX Tcase[3]	Intel740 chip Tcase[4]	Memory Ambient[5]	Memory Avg. Air Velocity	Add-in Card Ambient
Specification			72	105	109	See Figure 3.2		55
Passive Heat Sink (standard)	Standard	Standard	99	NM[6]	NM	NM	NM	NM
Fan Heat Sink	Standard	Standard	97	NM	NM	NM	NM	NM
Small LPFD	PSU 2	Standard	66	104	105	44	NM	55
HFHS	PSU 2	Standard	61	100	90	44	NM	43
Small LPFD	PSU 1	Standard	61	100	96	40	282	63
HFHS	PSU 1	Standard	60	92	90	44	NM	64[7]
HFHS	PSU 1	Modified	60	90	88	44	NM	42[7]
Large LPFD	PSU 3	Standard	64	100	104	46	572	NM
HFHS	PSU 3	Standard	68	102	110	51	811	NM

Notes: 1 - Vent placement, either standard or modified. September 1998

2 - CPU plate temperature running KPOWER.exe.

3 - BX case temperature running BTTS01.exe /u2.

4 - Intel740 chip case temperature running Therm740.exe.

5 - Memory ambient taken from maximum of KPOWER, or BTTS01 /u2.

6 - NM - indicates “not measured.”

7 - Add-in card measurement with one probe instead of standard four-probe measurement.

The "as received" standard configuration obviously is not a viable thermal solution because the processor exceeds the maximum temperature by 26 °C, exposing the weakness of the standard power supply and chassis airflow impedance.

Implementing the fan heat sink, the processor exceeds the maximum temperature specification by almost 25 °C. The ambient inlet temperature to the fan heat sink is approximately 55 °C which is 10 °C above the maximum specified temperature. Indicating this particular chassis requires more airflow and a cooler internal ambient temperature than the standard power supply can deliver. The active processor fan heat sink will have a much higher probability of cooling the processor and system if either PSU 1 or PSU 2 is installed. However, PSU 1 is the best choice because the vents would point directly at the processor, chipset, and memory.

As mentioned in Section 4.4, two early prototype LPFDs are evaluated. Please refer to the LPFD specifications and the reference design shown in Figures 4.5 through 4.7 for information on implementing the LPFD in a system.

Both the small and large LPFDs cool the core logic components below the maximum temperature specifications. However, the power supply choice does affect system temperatures when the LPFD is implemented. Notice the 5 °C (66 °C to 61 °C) decrease in the processor temperature between PSU 2 and PSU 1 with the small LPFD, but the largest effect may not be immediately obvious. Comparing the large LPFD/PSU 3 combination and the small LPFD/PSU 2 combination, the processor thermal plate temperature decreases 2°C (64 °C vs. 66 °C) with the large LPFD/PSU 3 combination. PSU 3 has similar venting to PSU 2 but the volumetric flow is approximately half (9 cfm vs. 16 cfm). The volumetric flow difference suggests PSU 2 should result in a lower processor plate temperature. However, the increased volume of the large LPFD (106% more inlet area than the small LPFD) compensates for the lower power supply volumetric airflow of PSU 3. This indicates the large LPFD significantly aids the power supply in cooling the core logic components and can "mask" the effects of a low performance power supply.

LPFD key learnings and recommendations:

- Heavily configured systems can be cooled with either the small or large duct.
- Power supply choice does affect cooling capacity but all three satisfy maximum temperature specifications.
- The inlet duct dimensions should be the maximum allowed in the Low Profile Fan Duct System Board and Chassis Specification (1.25 in x 5.165 in).

HFHS also cools the core logic components below maximum temperature specifications. The power supply selection is more pronounced with the HFHS though. Comparing the HFHS with PSU 1, PSU 2, and PSU 3 shows this difference well. PSU 1 cools the processor to 60 °C, PSU 2 cools the processor to 61 °C, and PSU 3 raises the processor thermal plate temperature to 68 °C. As mentioned before, PSU 2 and PSU 3 have similar vent locations but PSU 2 delivers approximately twice as much airflow as PSU 3, resulting in the lower temperature.

HFHS key learnings and recommendations:

- Heavily configured systems can be cooled.
- Power supply choice affects cooling capacity significantly.

RDRAM, at the time of testing, requires local ambient temperatures and local airflow measurements to determine thermal compliance as mentioned in Section 3.4.3. As illustrated in the table, the minimum local airflow provided by the HFHS or LPFD is approximately 282 lfm and the maximum ambient temperature is 51 °C. LPFD provides a lower ambient temperature with less airflow whereas HFHS provides a higher ambient temperature but compensates with much higher local airflow. Referring to Figure 3.2, the RDRAM junction temperature should be well below the maximum 100 °C specification. Local airflow velocities are not measured for the active processor fan heat sink because the processor ambient inlet temperature exceeds the maximum specified value by 10 °C.

Add-in card ambient temperatures are marginal or exceed the guideline in most of the cooling methods in this mid-tower chassis. The standard vent design on the chassis incorporates a side vent located approximately 2 inches forward from the back and 2 inches higher than the bottom of the chassis as shown in Figure 4.12. Considering the high temperatures the add-in cards experience, the vent is relocated as shown in Figure 4.13. This relocation biases the vent location towards the rear of the chassis directly over the add-in cards. Since the power supply evacuates the chassis, the vent draws cool external air from the surroundings over the add-in cards. The decrease in add-in card ambient temperatures is significant at 22 °C (42 °C vs. 64 °C) proving that proper vent size and location is critical to proper cooling.

4.7.2 Mini-Tower Chassis

Table 4.3 compares cooling methods proposed for the heavy load mini-tower configuration.

Table 4.3: Mini-Tower Chassis (Heavy Load)

Cooling Method	**Power Supply**	**Vent Pattern[1]**	**CPU Tplate[2]**	**82443BX Tcase[3]**	**Intel740 chip Tcase[4]**	**Memory Ambient[5]**	**Memory Avg. Air Velocity**	**Add-in Card Ambient**
Specification			72	105	109	See Figure 3.2		55
Power Supply Duct	PSU 1	Standard	65	113	95	43	42	40
Fan Heat Sink	PSU 1	Standard	73	65[6]	NM[7]	51	NM	42
HFHS	PSU 1	Standard	62	94	93	45	300	52
Small LPFD	PSU 1	Standard	75	96	112	56	NM	71
Small LPFD	PSU 2	Standard	62	96	96	47	191	52

Notes: 1 - Vent pattern, no vent modifications implemented. September 1998

2 - CPU plate temperature running KPOWER.exe.

3 - 82443BX case temperature running BTTS01.exe /u2.

4 - Intel740 chip case temperature running Therm740.exe.

5 - Memory ambient taken from maximum of KPOWER, or BTTS01 /u2.

6 - 82443BX case temperature running KPOWER.exe.

7 - NM indicates “not measured.”

The mini-tower chassis evaluated comes standard with a duct on the power supply to direct air over the processor, chipset, and memory. This standard duct works well for cooling the system. The only component above the maximum temperature specification is the 82443BX Host Bridge/Controller at 112 °C. Understand that the chip is dissipating 6.5 W during this measurement rather than the published thermal design power of 4 W. The memory local ambient air temperature is cool at 43 °C but the airflow is low at 42 lfm. RDRAM memory may possibly be bandwidth limited at worst-case power dissipation conditions.

The active processor active fan heat sink ambient inlet temperature is approximately 50 °C which is 5 °C above the specification. Consequently the fan heat sink can not compensate for the increased inlet temperature and the processor thermal plate temperature exceeds specification by 1 °C. The other system components however are cooled below specification. The RDRAM memory may be bandwidth limited because of the high local memory ambient temperature. Unfortunately, local airflow velocity is not measured but most likely approximates the velocity the standard duct provides.

HFHS cools all of the components below the maximum temperature specifications including RDRAM. The memory local ambient temperature is 45 °C and the airflow is 300 lfm which will cool the RDRAM well below the 100 °C junction temperature specification (refer to Figure 3.2).

LPFD is significantly affected by the power supply choice. When PSU 1 is implemented, the LPFD blocks the vent (top face shown in Figure 4.9) on the power supply and thus reduces the airflow into the supply (supply is evacuating). The processor, chipset, and add-in card temperatures subsequently rise above specification to almost 75 °C, 112 °C, and 71 °C, respectively illustrating the necessity to choose the correct power supply to provide adequate airflow throughout the system in conjunction with the LPFD. When the correct supply is chosen (PSU 2 because the vents are not blocked), the airflow is more than adequate to cool all of the key components as shown by the processor dropping 13 °C.

Some of the proposed cooling methods described satisfy the maximum temperature specifications published for the key components and each has its positive and negative properties that must be evaluated by the designer. The standard duct actually cools the system well but may limit RDRAM bandwidth under worst case conditions. The active processor fan heat sink is the easiest to be implemented and the lowest cost but due to the 50 °C ambient inlet temperature does not cool the processor below specification. Other enhancements would be necessary to implement this solution in the system. HFHS and LPFD both cool very well but have design issues to overcome such as motherboard or chassis dependence. The designer must evaluate all the options available and decide which method will work the best for the design in question because more than one solution is available.